

**BUZZWEAR: SUPPORTING MULTITASKING WITH WEARABLE  
TACTILE DISPLAYS ON THE WRIST**

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# **BUZZWEAR: SUPPORTING MULTITASKING WITH WEARABLE TACTILE DISPLAYS ON THE WRIST**

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*To my family and husband,*

*who are 7,000 miles away.*

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## SUMMARY

On-the-go users' interaction with mobile devices often requires a high level of visual attention that can overtax limited human resources. For example, while attending information displayed on a mobile device, on-the-go users who are driving a car or walking in the street can easily fail to see a dangerous situation.

This dissertation explores the benefits of wearable tactile displays (WTDs) to support eyes-free interaction for on-the-go users. The design and implementation of the WTDs are motivated by two principles in mobile user interaction that have been proven both commercially and academically: wristwatch interfaces that reduce the time for device acquisition and tactile interfaces that eliminate the need for visual attention.

In this dissertation, I present three phases of design iteration on WTDs to provide the design rationale and challenges. The result of the iterative design is evaluated through in-depth formal investigations with novice users in two experiments: user perception of the tactile stimuli and information throughput in association with multiple tactile parameters, and perception of the tactile stimuli and information throughput when the user is visually distracted.

The first experiment explores general human capabilities in perceiving tactile stimuli on the wrist. It reveals that subjects could discriminate 24 tactile patterns with 98% accuracy after 40 minutes of training. Of the four parameters (intensity, starting point, rhythm, and direction) that were configured to design the 24 patterns, intensity was the most difficult parameter to distinguish, and rhythm was the easiest.

The second experiment explores users' abilities to perceive incoming alerts from two mobile devices (WTD and mobile phone) with and without visual distraction. Compare to the mobile phone alert perception which becomes slower and less accurate when visually distracted, alert perception through the WTD is less affected by visual distraction.

# CHAPTER I

## INTRODUCTION

### **1.1 Motivation**

Multitasking is becoming more common in almost all activities in our lives [50] such as domestic household activities [92] and media consumption [31]. Mobile computing implies multitasking [90], and interacting with mobile devices while on-the-go has led to controversy.

When interaction with mobile devices requires visual attention, the device and the surrounding environment often compete for the user's attention. Recent reports warn that on-the-go mobile interaction is associated with dangerous levels of distraction. Visual engagement with mobile devices while operating vehicles [15, 17] or walking in the street [100] often threatens the safety of the user as well as that of other people.

In some countries and states, the use of handheld devices and receiving or sending text messages on mobile phones are prohibited by the law (<http://www.distraction.gov/state-laws/>). However, anecdotal reports of everyday mobile interaction indicate that people continue these practices. Legal regulation may prove insufficient to change the usage of mobile devices in the field. In this dissertation, I take a different approach by investigating the design of more multitasking-friendly mobile user interfaces (UIs) as a means for creating safer mobile devices.

#### **1.1.1 The need for multitasking-friendly mobile user interfaces**

Problems in multitasking while on-the-go are usually caused by limited attention and dexterity. Attention and dexterity are often divided among tasks while using mobile devices (e.g., when receiving a phone call while driving a car). Since humans have limited attention and dexterity, mobile interactions may overwhelm our capabilities when we attempt to perform multiple tasks, whether simultaneously or successively. Such limitations, which have been referred to as situationally induced impairments and disabilities (SIID) [107], are one of the biggest challenges in mobile user interaction.

What are the challenges in mobile multitasking, and what should be investigated to design multitasking-friendly mobile devices? Researchers have explored several issues to be considered while designing multitasking-friendly mobile UIs, such as proximity between the user and the devices [96], access time for device acquisition [2], resource management when shifting attention between multiple tasks [90], and alternative modalities for reducing attentional workload [9, 14].

### **1.1.2 Two promising approaches: tactile and wearable UIs**

As the computing environment moves from desktop to mobile, the difference between desktop and mobile interaction should be clearly understood in order to design appropriate UIs. In a desktop computing environment, the sense of touch has been relatively under-utilized in UI design for information presentation when compared to visual and auditory displays. One of the reasons may be the lack of need to supplement the audio-visual channel in a desktop computing environment because attentional resources for these senses are relatively steady; adding a tactile channel is unnecessary.

In a mobile computing environment, sensory distraction in the audio-visual channels occurs more frequently than in a desktop computing environment. As a consequence, the availability of audio-visual attention is somewhat temporary and restricted. The widespread use of vibrating alerts in mobile phones shows that alternative channels are especially beneficial in a mobile computing environment. Furthermore, because tactile stimulation can be perceived through the skin over the entire body, utilizing this under-used sense may be the key to maximizing attentional resources [35].

In addition to sensory distraction, motor distraction is another factor that should be investigated in mobile interaction. While users are on-the-go, mobile devices are not readily available for interaction because users' hands are often engaged with other tasks. For on-the-go users, the additional workload, both physical and temporal, of acquiring devices from bags or pockets, tends to result in reluctance to use the device [111]. Compared to handheld counterparts, wearable interfaces that are in close proximity with the body reduce device access time significantly [2]. The recent commercialization of wearable interfaces such

as wristwatch phones [131], wristwatch camcorders [82], and vibrating wristbands [30, 59] reflects the emerging trend towards ready-at-hand mobile interactions.

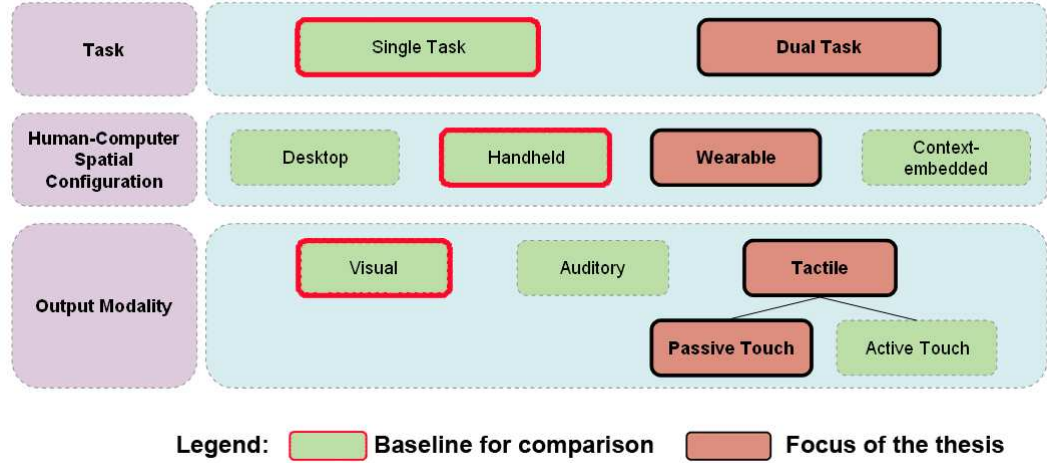
In this dissertation, I explore how integration of these two promising trends — utilization of the sense of touch and the wearing of wristwatch interfaces — can facilitate mobile interaction with limited audio-visual distraction. Specifically, I focus on the users’ capability to perceive alerts. This dissertation explores the design and evaluation of wrist-mounted wearable tactile displays (WTDs) and tactile patterns that are expected to enable vision-free alert perception for on-the-go users.

Similar to information visualization, which presents information through visual elements, the presentation of information through the sense of touch is called information tactilization or hapticization. Information tactilization refers to the perception of information that is conveyed through the incoming tactile stimulation (passive touch) [13], whereas information hapticization refers to the perception of information that is combined with the sense of touch and kinesthetic exploration or manipulation of the body (active touch) [29]. Since I focus on the perception of tactile stimuli on the wrist, more sophisticated factors [77] in designing tactile information for information tactilization and hapticization, such as learning a mapping from tactile patterns to meanings (tactile icons), are not included in this thesis.

## ***1.2 Purpose of research***

The goal of this research is to explore the benefits of WTDs in reducing visual distraction in mobile computing. As highlighted in Figure 1, this dissertation focuses on the design of WTDs that use passive tactile stimuli on the wrist to enable alert perception with little audio-visual distraction. To compare the benefit of WTDs with existing mobile interactions, I measure users’ performance with commercial handheld devices where equivalent information is presented visually.

I have chosen to place my WTD on the wrist because the wrist is a socially acceptable place to wear devices (for example, wristwatches and bracelets) [93] and the device is available immediately for interaction [2]. I selected visual distraction because vision is currently



**Figure 1:** Research focus.

the most dominant channel through which information is presented during mobile interaction, and it may most threaten the safety of on-the-go users [107, 120]. In addition to dual task performance with visual distraction, single task performance is explored to provide a baseline reference.

### 1.3 Thesis statement

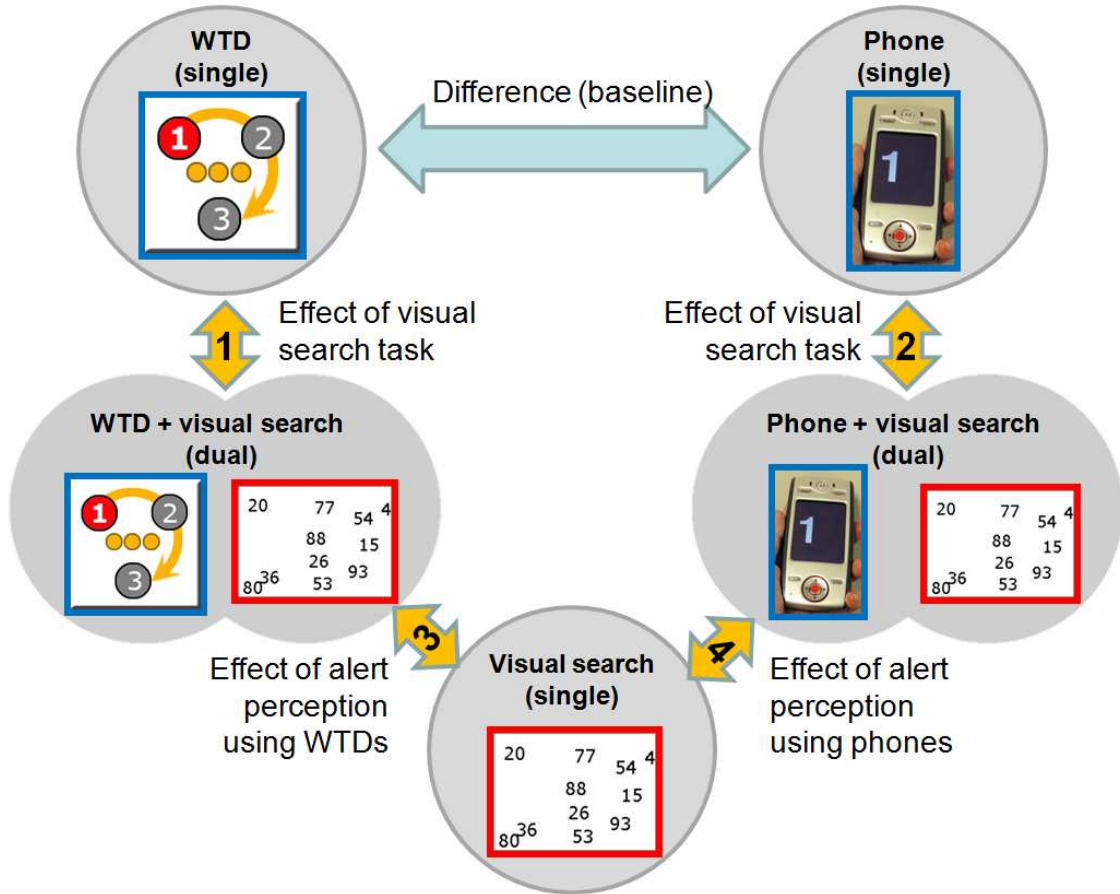
I hypothesize that WTDs will facilitate alert perception with mobile devices by reducing the need for visual attention and device acquisition time.

### 1.4 Research questions

This thesis will explore the following research questions:

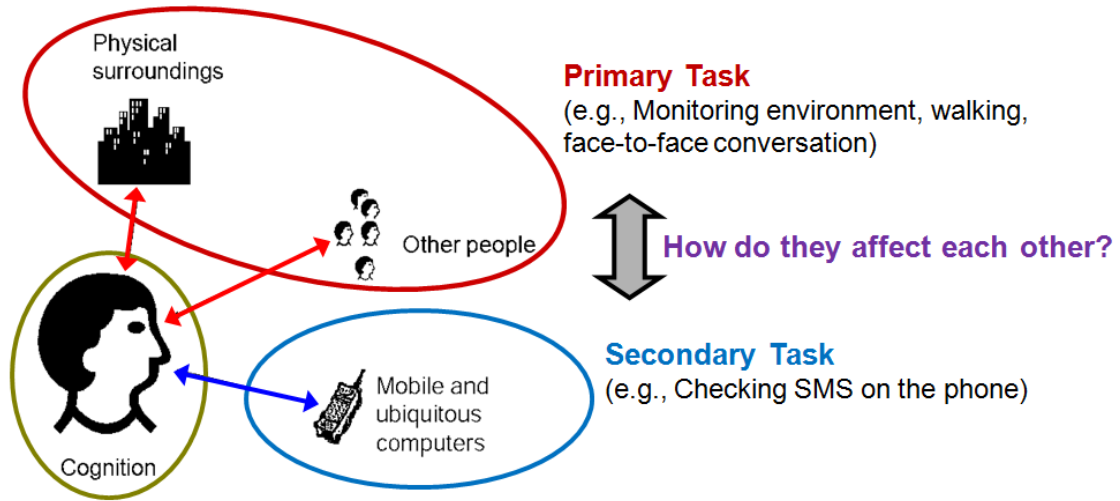
1. Can a WTD on the wrist be an appropriate interface to present tactile stimuli?
  - (a) With less than an hour of training, can people successfully detect tactile patterns on the wrist?
  - (b) Can people differentiate multiple parameters of tactile sensation simultaneously?
2. Can tactile alerts on WTDs be perceived while the user is visually distracted?

- (a) How much is the secondary task (alert perception with a WTD or a mobile phone) affected by the primary task (visual search task)? (Figure 2, arrow 1 & 2)
- (b) How much is the primary task (visual search task) affected by the secondary task (alert perception with the WTD and the mobile phone)? (Figure 2, arrow 3 & 4)



**Figure 2:** Research question focus: The effect of primary task on secondary task (arrow 1 & 2), the effect of secondary task on primary task (arrow 3 & 4).

Research question 1 explores the general design of wrist-mounted WTDs and the perception of tactile stimuli on the wrist. The design of WTDs and tactile patterns that utilize four patterns (starting point, intensity, rhythm, and direction) are explored.



**Figure 3:** Methodological approach in assessing the benefit of WTDs (modified from Oulasvirta [89]).

Here and throughout the thesis, I define two main concepts that are associated with mobile interaction, the *primary* and *secondary* tasks (Figure 3), as follows:

- The *primary* task encompasses activities that are involved in interaction between the user and the environment such as walking, screening the environment, and engaging in face-to-face communication.
- The *secondary* task encompasses activities that are involved in interaction between the user and mobile devices such as controlling an MP3 player, checking an SMS on a phone, or answering an incoming phone call.

Research question 2 focuses on the benefit of using WTDs to enable eyes-free alert perception (secondary task) in visually distracted conditions (primary task). Both primary and secondary tasks are performed independently (single task condition) and while combined with each other (dual task condition). In addition to the performance using WTDs, performance using commercial mobile phones is explored in order to compare the alert perception through WTDs with current practice.

## **1.5 Research contributions**

The broad contribution of this dissertation is to provide guidelines for multitasking-friendly WTDs and tactile pattern design. Relevant research communities include human-computer interaction, wearable computing, and psychophysics. Research contributions include

1. **Tactile Pattern and Display Design:** Through iterative design and pilot studies, I demonstrate constraints to the design of tactile patterns including the skin’s sensitivity to vibro- and electrostimulation, limitations to the actuation speed of off-the-shelf vibrators, and parameters that can be used effectively in creating tactile patterns (i.e., starting point, rhythm, direction, and intensity).
2. **An exploration of users’ perceptions of tactile patterns using a wrist-mounted, three-vibrator display:** I perform a user study of 24 tactile patterns, composed by varying the four parameters above, and measure accuracy, reaction time, confusability, information transfer rate, and subjective measures. Given these results, I provide recommendations on which parameters to vary to provide the clearest perception of tactile patterns.
3. **A comparison of the perception of alerts presented using a WTD versus current practice (a mobile phone) while the user is distracted visually:** I examine the effect of three difficulty levels of visual distraction on 16 users’ perception of three alerts presented using a tactile display or a mobile phone. I also examine the effect of receiving the alerts on the users’ ability to perform the visual task. I report on users’ preferences, strategies, and subjective workload while attempting to perform multiple tasks.

## **1.6 Thesis overview**

Chapter 2 introduces background research that presents various aspects of tactile communication (i.e., tactile physiology, perception, UI design, and information transmission) and human performance in dual task conditions (i.e., management of attentional resources and modality configuration).



In Chapter 3, three phases of design iteration with pilot studies illustrate various successes and failures in the design of both WTDs and tactile patterns. In each pilot study, detailed aspects of the design are tested and iterated upon to improve the system. The final design of Phase 3 is used for the formal investigation in Chapter 4 and Chapter 5.

In Chapter 4, I present a user study on users' perception of 24 tactile patterns on the wrist designed by manipulating four distinct parameters: intensity, rhythm, direction, and starting point. Quantitative performance as well as subjective results are assessed to explore whether the tactile patterns are easy to perceive.

In Chapter 5, I explore the effect of tactile displays in visually distracted conditions. The ability to perceive patterns from a WTD with and without visual distraction is measured and compared. To compare the contribution and benefit of the WTD with current practice, I measure the performance on the same task using a mobile phone. A visual search task is designed with three levels of difficulty (easy, moderate, and difficult) and an alert perception task is performed with the WTD and a phone. The tasks are performed both independently (single task conditions) and in combination with each other (dual task conditions) resulting in eleven conditions. Quantitative performance data and subjective opinions on strategies for managing workload are collected for each given condition.

Chapter 6 presents ergonomics and survey data from the experiment.

Chapter 7 and Chapter 8 present a discussion on design implications for future work and the conclusion, respectively.

Table 1 provides an overview of the research questions. Subquestions, hypotheses, study method, data, and the analysis plan for each research question are included.

**Table 1:** Summary of research questions and studies

<b>Research Question</b>	<b>Hypothesis</b>	<b>Method</b>	<b>Data Collected</b>	<b>Analysis</b>
<p>Research Question 1</p> <p>subpart:</p> <p>A. Are tactile displays appropriate to deliver easy-to-perceive attentional and directional cues on the wrist?</p> <p>B. Can people easily differentiate multiple parameters of tactile sensation simultaneously?</p>	<p>I hypothesize that wrist-mounted WTDs are appropriate to deliver tactile patterns.</p>	<p>Adults participate while in controlled settings (within-subject). Participants are asked to discriminate four parameters simultaneously to perceive 24 tactile patterns on the wrist. Each pattern is generated through eight sets of repetitions to explore the learning curve.</p>	<p>1. Speed and accuracy of alert perception (quantitative).</p> <p>2. Learning curve (quantitative).</p> <p>3. Difficulties in perceiving each parameter in tactile patterns (quantitative, qualitative).</p>	<p>1. Exploring the accuracy and reaction time of novice users in perceiving 24 patterns.</p> <p>2. Exploring difficulties in discriminating four parameters presented in each pattern.</p> <p>3. Exploring learning effect.</p> <p>4. Assessing user-constructed strategies.</p>
<p>Research Question 2</p> <p>subpart:</p> <p>A. How much is the secondary task (alert perception) affected by the primary task (visual search task)?</p> <p>B. How much is the primary task (visual search task) affected by the secondary task (alert perception)?</p>	<p>I hypothesize that the alert perception through WTDs is 1) less distracted by the primary task and 2) less distracting to the primary tasks than existing mobile phone alerts.</p>	<p>Adults participate in controlled settings (within-subject) and perform in five single task and six dual task conditions. Single task is composed of the primary task with three difficulty levels (easy, moderate, difficult) and secondary task with two devices (perceiving alert from a WTD and a mobile phone). Dual task is composed of the combination of one primary task and one secondary task.</p>	<p>1. Speed and accuracy of alert perception in single and dual task conditions (quantitative).</p> <p>2. Speed and accuracy of visual search task in single and dual task condition (quantitative).</p> <p>3. Performance difference of the primary task caused by the secondary task, and vice versa (quantitative).</p> <p>5. NASA-TLX workload assessment (quantitative).</p> <p>6. Semi-structured interview (qualitative).</p>	<p>1. Calculate the performance difference of the accuracy and reaction time for the secondary tasks in single and dual task condition to learn the effect of the primary task, and vice versa.</p> <p>2. Assessing user-constructed strategy, if any, through interview.</p> <p>3. Assessing the workload of each condition through NASA-TLX and interview.</p>

## CHAPTER II

### RELATED WORK

#### *2.1 Touch as a communication channel*

This section provides basic definitions and describes the anatomy related to tactile sensation. It discusses related phenomena in tactile perception, types of tactile displays and tactile communication systems that are associated with information transmission.

##### **2.1.1 Tactile physiology**

Sensory stimuli, such as touch, sound, and light are transmitted to the nerve system through sensory receptors. Different types of stimuli are detected by different receptors [46] (Table 2). When the skin is deformed, mechanoreceptors fire, passing an alert through the nervous system.

Four main types of mechanoreceptors — Meissner corpuscles, Merkel cells, Ruffini endings, and Pacinian corpuscles — sense contact with the skin. The distribution of the skin deformation excites different types of mechanoreceptors depending on the characteristics of the stimulation.

Based on the pace of excitation, mechanoreceptors are classified into two types: rapidly adapting (RA) and slowly adapting (SA) mechanoreceptors (Table 3). RA mechanoreceptors respond best to higher frequency stimulation, whereas SA mechanoreceptors respond best to low frequency stimulation. The area to which a particular mechanoreceptive neuron responds is called its receptive field. Based on the size of the receptive field, mechanoreceptors are classified into two types; type I mechanoreceptors have a small receptive field and type II mechanoreceptors have a large receptive field. Type I mechanoreceptors (small receptive field) are known to be suitable for fine spatial discrimination. In general, the receptive field becomes larger as the mechanoreceptor is located deeper in the skin layer [98].

The skin layer is composed of three parts: epidermis, dermis, and subcutaneous fat

**Table 2:** Types of sensory receptors

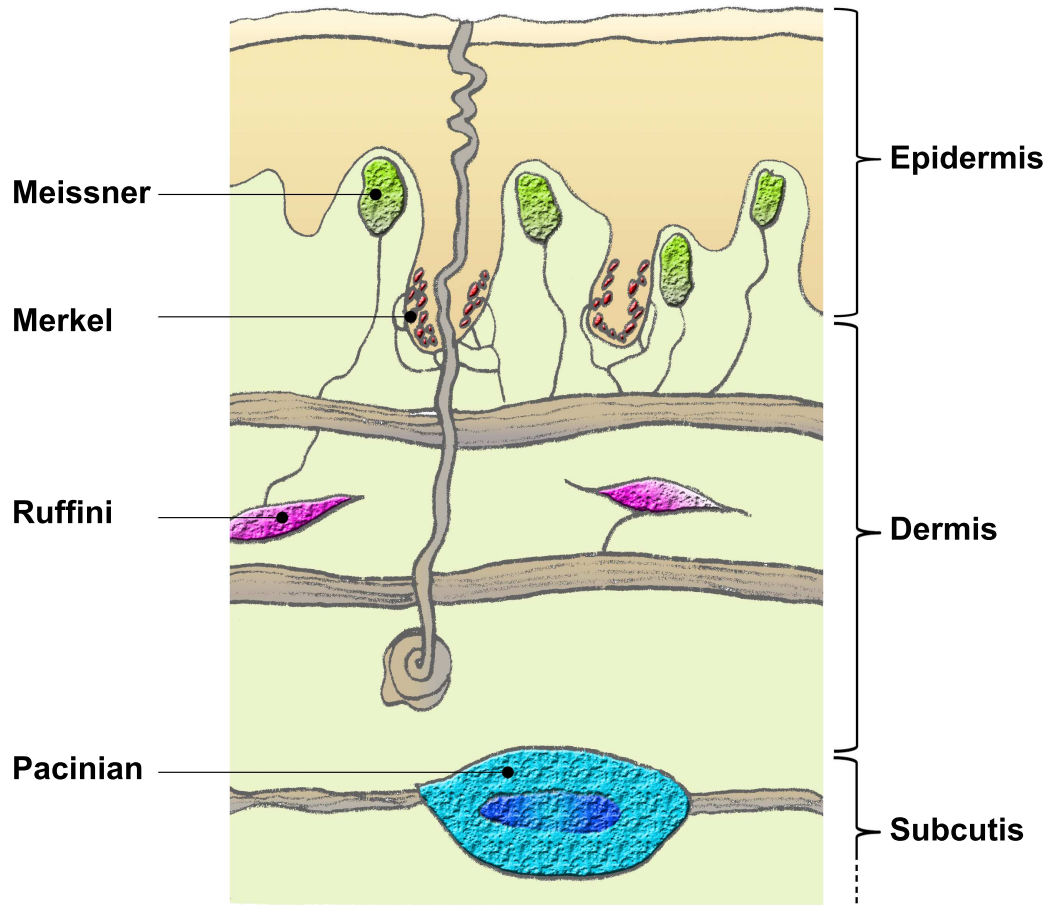
Types of sensory receptor	Relevant input
Mechanoreceptors	Mechanical deformation of cells
Thermoreceptors	Changes in temperature
Nociceptors (pain receptors)	Damage in tissues (physical or chemical)
Electromagnetic receptors	Light on the retina of the eyes
Chemoreceptors	Taste in the mouth, smell in the nose, oxygen level in the arterial blood, and other chemistry of body

**Table 3:** Types of mechanoreceptors

		Pace of excitation	
		Rapidly adapting (RA)	Slowly adapting (SA)
Receptive field	Small (Type I)	<b>RAI</b> <b>(Meissner corpuscles)</b>	<b>SAI</b> <b>(Merkel cells)</b>
	Large (Type II)	<b>RAII</b> <b>(Pacinian corpuscles)</b>	<b>SAII</b> <b>(Ruffini endings)</b>

(Figure 4). Epidermis is the outermost layer that does not contain blood vessels. Dermis is the middle layer that contains blood vessels, nerves, sweat glands, and hair roots. The deepest layer is subcutaneous fat, of which the depth differs from person to person. The Meissner corpuscles (RAI) are located near the boundary of epidermis and dermis. Merkel cells (SAI) and Ruffini endings (SAII) are located in the dermis layer. Pacinian corpuscles (RAII) lie deeper than other mechanoreceptors.

Pacinian corpuscles (RAII) detect tactile stimulation ranging from 50 to 1000 Hz and are especially sensitive to vibrations between 250 and 350 Hz [98]. High frequency vibration and deep pressure are mostly detected in association with a relatively large receptive field [110, 47]. Meissner corpuscles (RAI) are sensitive to light touch or lower frequency vibration between 30 and 70 Hz. The receptive field of Meissner corpuscles is smaller than that of Pacinian corpuscles [98, 47]. Merkel cells (SAI) detect steady skin indentation such as that caused by the form and texture of objects [57]. The receptive field of Merkel cells ranges from 3 to 4 mm in diameter and responds best to frequencies between 2 to 32 Hz [55]. Although Ruffini endings (SAII) have been known to mediate the perception of directional



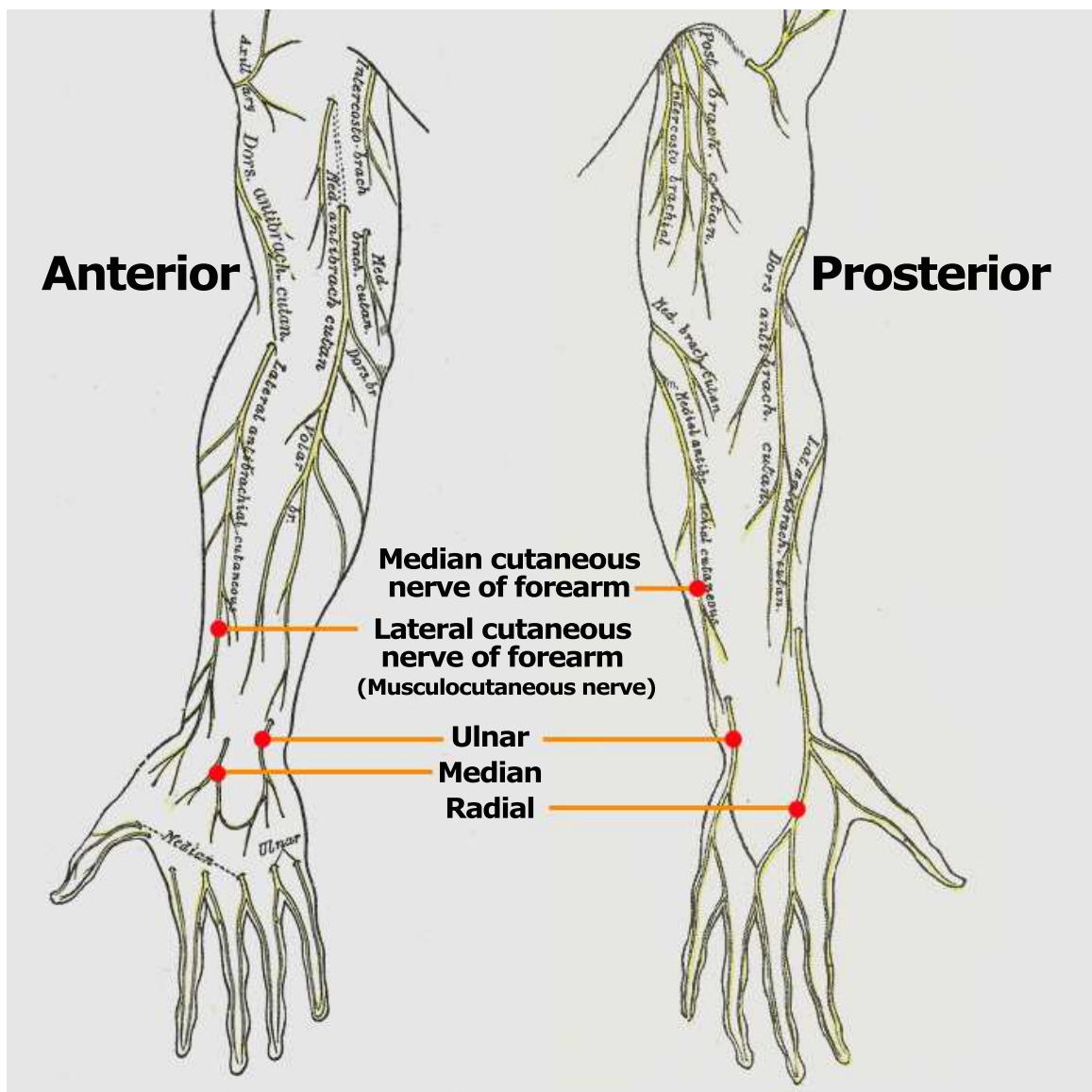
**Figure 4:** Mechanoreceptors of human hairless skin (adapted from Poletto [98]).

skin stretch [56, 87], the perceptual profile of Ruffini endings has been less studied than other mechanoreceptors.

The distribution of the nerve fibers along the anterior and posterior portion of the forearm and wrist is slightly different (Figure 5). In each side of the forearm, three types of nerve—radial, median, and ulnar—play different roles [46].

The radial nerve enters the forearm and continues into the posterior side of the thumb and fingers. In association with muscular activities, the radial nerve is engaged in the movement of the forearm and fingers such as extension of the elbow, wrist, fingers, and thumb, supination of the forearm and hand, and abduction of the thumb. The median nerve, on the other hand, passes the anterior portion of the forearm, thumb, and first three

fingers. The muscular activities that are associated with the median nerve are flexion of the wrist, fingers and thumb, abduction of the wrist and thumb, and opponens of the thumb. The ulnar nerve passes both the anterior and posterior surface of the little finger and the medial half of the third finger. The ulnar nerve provides cutaneous sensation along the surface of the third and little finger. The ulnar nerve is also known to be the largest nerve in the human body that is not protected by bone or muscle. The muscular activities in which the ulnar nerve is engaged are the flexion of the wrist and fingers, abduction of the fingers and thumb, and opponens motion of the little finger.



**Figure 5:** Nerve distribution in wrist area (adapted from Gray [44]).

### 2.1.2 Tactile perception

In contrast to vision or hearing, the sense of touch is highly proximal. Tactile sensation is also multifunctional in that its capability supports both perception (passive touch) and manipulation of objects (active touch). Active touch represents the exploratory action of touching, which is generally involved with kinesthetic movement of the body; passive touch refers to stimulation of the skin that is delivered from an outside agent. The focus of this dissertation is limited to passive touch.

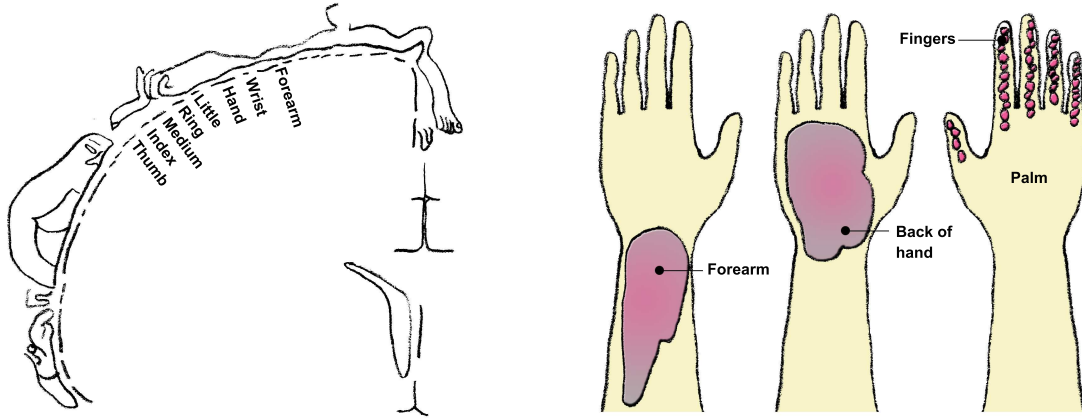
Tactile perception is often distinguished from haptic perception, which is associated with kinesthesia [95, 98]. Kinesthesia relates to the relative positioning and movement of body parts with regard to muscular effort while touching or manipulating objects. When tactile perception, which includes skin stretch, vibration, pressure, and contact force, is combined with kinesthetic perception, the result generally conveys a felt object’s properties such as shape [73]. In this paradigm, passive touch is associated with cutaneous or tactile sensation, whereas active touch implies proprioception or haptic sensation.

#### 2.1.2.1 Sensory parameters

Perception of tactile stimuli depends on various factors, such as the characteristics of the stimuli for coding tactile texture (e.g., intensity, frequency, temporal coding, spatial coding, and spatio-temporal coding [94, 97]), placement, gender, and age [126]. Humans can perceive vibrations between 20 and 1000Hz. The maximum sensitivity for vibro-tactile sensation at the first metacarpal of the right hand on the palm side was observed at around 250Hz [123]. The ability to discriminate frequencies increases when presented in a relative way rather than an absolute way [9]. In discriminating intensity, the just noticeable difference (JND) has been reported with various values, ranging from 0.4dB to 3.2dB [45].

As illustrated in Figure 6 [109], sensitivity to tactile stimuli and nerve distribution (Figure 5, [44]) varies across the body. In general, fingers are more sensitive than the forearm or the back of the hands. Based on Vierordt’s Law of Mobility (1870), the perception of localized vibro-tactile sensation is higher when presented near anatomical points of reference such as the elbow, spine, or wrist [19, 80].





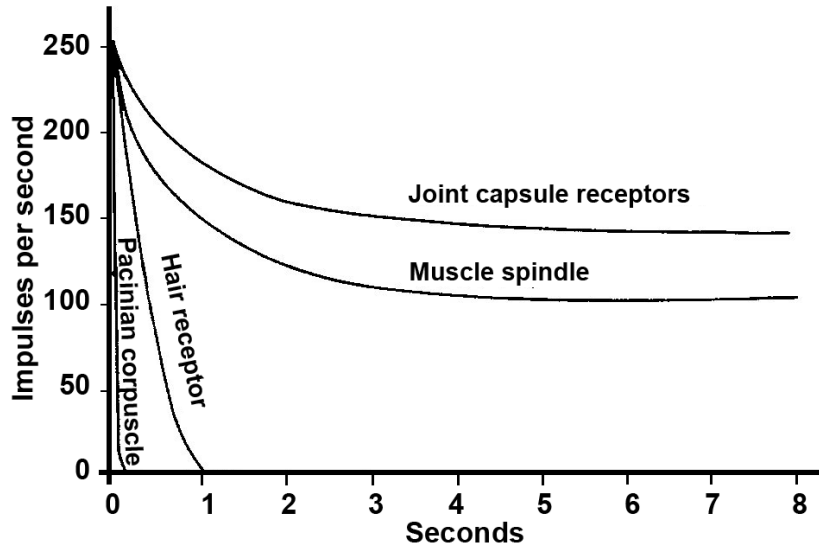
**Figure 6:** Human body and the perception of touch (adapted from Schiffman [109]): Sensory homunculus of the human body with hand, wrist and forearm projected on the cross section of the somatosensory cortex. The size of each part represents the perception sensitivity (left). The right images show the receptive field of the hand and arm. The volar side of the fingers are more sensitive than the back of the hand or forearm.

Regarding the spatial configuration of vibro-tactile displays, Oakley et al. [83] revealed that vibro-tactile alert perception across the back of the hand (from thumb to pinky) is easier than perception along the back of the forearm (from wrist to elbow). Chen et al. [16] explored tactor localization at the wrist using an array of 3x3 positions. They discovered that three is the maximum number of locations that people can identify with minimal confusion using an inverted triangular layout at the volar side of the wrist or a triangular layout at the dorsal side of the wrist.

Studies reveal that spatial and temporal patterns are easier to discriminate than frequency and intensity [10, 36]. This limitation is due to the skin being poor at recognizing differences in frequency, and sensitivity to intensity differs across body location [58].

The temporal duration of the stimulation generally determines the quality of sensation [45]. Vibro-tactile stimuli lasting less than 100ms are perceived as taps or jabs against the skin. Stimuli with longer duration are generally combined with gradual attack or decay and are perceived as a tactile sensation akin to something rising out of the skin. Thus, manipulation of temporal patterns can generate different textures of tactile sensation in addition to creating a tactile rhythm with temporal variations.





**Figure 7:** Adaptation effect (adapted from Guyton [46]) of different types of receptors.

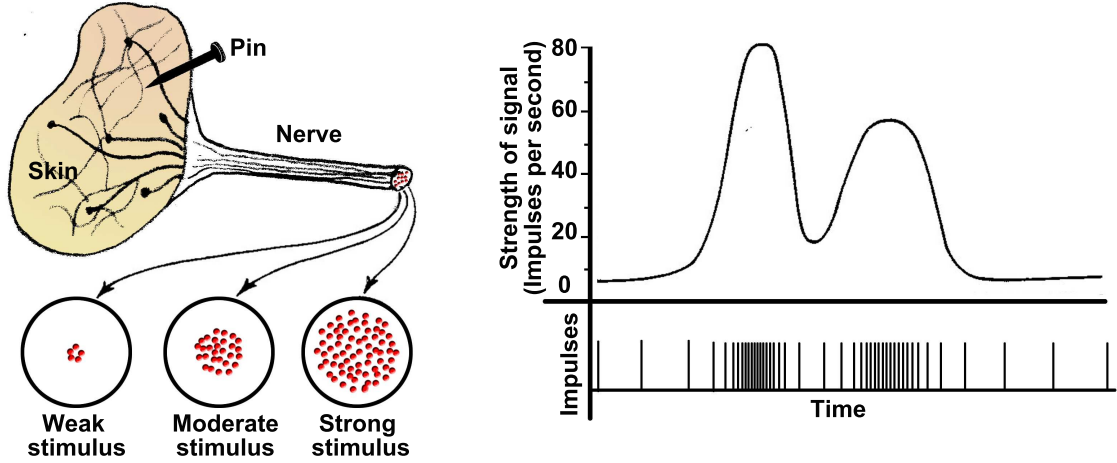
#### 2.1.2.2 Sensory phenomena

When multiple actuators are arranged in a two-dimensional array, a temporal pattern can be easily associated with a spatial pattern. Temporal and spatial parameters can be manipulated to create various sensory phenomena. Such phenomena include masking, adaptation, enhancement, change blindness, and sensory saltation [38, 95, 108].

*Masking* refers to the phenomenon that the presentation of masker stimuli hinders the correct perception of following target stimuli [20, 25]. To avoid the masking effect, increasing the interval between stimuli and the spatial distance between maskers and the targets is suggested [25].

*Adaptation* is reduced perception caused by continuous exposure to a vibro-tactile stimulus above the perception threshold. The effect is temporary and disappears if proper time gaps are provided between stimuli. When a continuous stimulus is applied, the response rate of the receptors is very high at first and progressively decreases to a lower rate until the receptors no longer respond. The adaptation effect is a special characteristic of sensory receptors. The adaptation rate of the Pacinian corpuscle, which is sensitive to vibration, is extremely fast (Figure 7, [46])

*Enhancement* is a perceived magnification of stimulation intensity caused by spatial or temporal summation. Spatial summation refers to an increasing number of stimulated nerved fibers that results in a perception of increasing intensity (Figure 8-left, [46]). Temporal summation refers to an increasing number of impulses along a single fiber which causes a perception of increasing intensity (Figure 8-right, [46]). Temporal summation is an opposite concept to adaptation with respect to continuously presented stimulation [42, 124].



**Figure 8:** Enhancement effect (adapted from Guyton [46]): Spatial summation (Left), Temporal summation (Right).

*Change blindness* is the failure to detect change between two consecutive stimuli. This phenomenon is a tactile equivalent of visual change blindness [33, 34].

*Sensory saltation* refers to the sensory illusion of stimulation that seems to move between multiple local points in the body [40]. In two-dimensional tactile displays, in addition to the two point discrimination threshold (TPDT) or JND (which is associated with the static localization of the perception), sensory saltation should be considered as a critical phenomenon to determine perception. As described by the “cutaneous rabbit” phenomenon [39], this tactile illusion is generated through a rapid sequence of tapping on separate regions of the skin. When the rapid sequence of taps is generated first near the wrist and then near the elbow, people perceive the taps between the two separate regions as directional motion hopping from the wrist to the elbow. This phenomenon allows the creation of directional displays where the perceived resolution of the display is higher than the actual density of

the display. Such sensory illusions can be created in visual and auditory modalities as well [112, 119].

Parameters that determine the quality of sensory saltation are the inter-stimuli-interval (ISI), saltatory area, repetition and regular training. The ISI is known as a crucial factor in affecting sensory saltation because the perceived displacement of one stimulus depends on the time interval to a subsequent stimulus presented at a separate location [18, 39, 40]. Generally, saltation increases when ISIs decrease. The effect of saltation generally disappears when the ISI is longer than 200ms. The skin area where the sensory saltation phenomenon occurs is referred to as the saltatory area. Although the size of the saltatory area is mostly determined by body placement, it can be modified by repeated stimulation as well [112, 119].

### **2.1.3 Tactile displays**

Tactile displays, which are composed of single or multiple actuators, utilize the sense of touch to render information. Researchers have explored the contribution of tactile displays in many areas such as sensory substitution for vision or hearing [3, 62], spatial orientation and navigation [71, 115, 122], and exploration of virtual environments to support augmented user experience or tele-manipulation [86].

In one-dimensional tactile displays, the characteristics of the stimuli are generally determined by intensity, frequency, and temporal patterns on a localized single tactile actuator. Two-dimensional tactile displays enable more sophisticated patterns by utilizing the spatial configuration of multiple actuators. In two-dimensional tactile displays, spatial patterns often involve a directional sensation in which the stimulation is generated in a sequential manner from locus to locus rather than in isolation.

Brown and Brewster [10] explored the recognition rate of 27 tactile patterns with three types of rhythms and three types of roughness that were generated on a single point actuator in three positions at the forearm. Chen et al. [16] explored the human capability to localize tactile stimulation in a 3x3 grid both on the dorsal and volar sides of the wrist. Borst and Baiyya [8] investigated the recognition accuracy of three parameters (position, direction,

**Table 4:** Comparison of various WTDs

Reference	Display size (layout)	Placement	Pattern design parameter	Display type
Brown et al. [10]	3 (linear)	Forearm	Roughness rhythm location	Vibro-tactile
Chen et al. [16]	9 (3x3 grid)	Wrist (dorsal & volar)	Location	Vibro-tactile
Borst et al. [8]	30 (5x6 grid)	Palm	Intensity direction location	Vibro-tactile
Ho et al. [51]	2 (polarized)	Torso (front & back)	Location	Vibro-tactile
VanErp et al. [122]	8 (linear)	waist	Rhythm location	Vibro-tactile
Lindman et al. [71]	8 (circular)	Torso (around)	Location	Vibro-tactile
Ng et al. [80]	2 (linear)	Forearm wrist	Rhythm location	Vibro-tactile
Ng et al. [80]	2 (linear)	Forearm wrist	Rhythm location	Electro-tactile
Bach-y-Rita et al. [3]	144 (12x12 grid)	Tongue	Not specified	Electro-tactile
Kajimoto et al. [62]	512 (16x32 grid)	Forehead	Location	Electro-tactile
Kume and Ohzu [65]	35 (5x7 grid)	Forearm	Location	Electro-tactile
Kume and Ohzu [65]	9 (3x3 grid)	Forearm	Location duration	Electro-tactile

and intensity) in a two-dimensional tactile display and revealed that people can interpret multiple parameters in combination. Ho et al. [51] explored the effect of vibro-tactile alerts on the front and back of the torso in a driving scenario. VanErp et al. [122] encoded real world spatial information (distance and direction) of an object using tactile stimulation (rhythm, location) in a waist belt tactile display with eight actuators. They revealed that rhythm is not effective for presenting distance information, whereas the location of actuators is effective for presenting direction information of a real world object. Table 4 summarizes these works, including the number of actuators, body placement, and parameters used for creating pattern designs.

Technologies for developing tactile displays are divided into two main categories: vibro-tactile and electro-tactile. Other technologies include pin arrays and piezoelectric actuators. Vibro-tactile displays stimulate the skin with mechanical actuators whereas electro-tactile

displays utilize the electric conductive capability of human skin.

In vibro-tactile displays, electrical energy is converted to a mechanical displacement of the actuator to generate a sense of touch on the skin. The advantages of vibro-tactile displays are easy fabrication and a robust sense of touch. That is, it is easy to control the vibrator to deliver a readily perceptible tactile sensation. However, when used in mobile conditions, the sense of touch from vibrating motors can be masked by kinesthetic movement of the human body [84].

In electro-tactile displays, current passes through surface electrodes, which are typically made of gold, platinum, silver, or stainless steel, and generates a tactile sensation on the skin. Because of different hydration levels and sensitivities of skin from location to location, the voltage to generate human-perceivable electro-tactile stimulation varies from 5V to 300V [61]. The fact that the electro-tactile display requires direct contact between the skin and the electrode is both an advantage and a disadvantage. Direct contact between the surface electrodes and skin receptors leads to a robust delivery of tactile sensation which is less susceptible to the movement of human body. However, compared to vibro-tactile displays, electro-tactile displays require much more sophisticated configurations for controlling the tactile texture. Once several electrodes lose tight contact with the skin, the intensity of the sensation for the rest of the electrodes can change and eventually generate sudden, uncomfortable sensations. The feeling delivered through the surface electrodes is qualitatively reported as a tingle, itch, buzz, or sharp and burning pain; it depends on the stimulating voltage, current and waveform, electrode size, skin location, and hydration level of the skin [61]. Thus, controlling the sensation at a comfortable level is challenging in the design of electro-tactile displays.

In a study that compared the vibro- and electro-tactile stimulation on the wrist and forearm [80], Ng et al. revealed that vibro-tactile stimulation on the forearm (VF) was easier to perceive than electro-tactile stimulation on the same location (EF). When comparing EF, VF, and vibro-tactile display on the wrist (VW), VF and VW were easier to perceive than EF, whereas no difference was observed when comparing an electro-tactile display on the wrist (EW) versus VW and VF.

Kume and Ohzu [65] developed a 5x7 electro-tactile array to display dot matrix style letters and numbers on the forearm. Users achieved 69% accuracy when the letters were presented through successive raster scanning (100 ms duration per dot with no ISI).

#### 2.1.4 Tactile information transmission

In many studies that explore the perceptual issues of tactile displays, information transfer ( $IT_{est}$ ) is calculated to assess the integrated perception performance of accuracy and reaction time (bits/second) [16, 114, 115].  $IT_{est}$  is beneficial to indicate the overall performance regardless of the typical speed-accuracy trade off.

$IT_{est}$  is generally calculated by

$$IT_{est}(bits) = \sum_{j=1}^k \sum_{i=1}^k \frac{(n_{ij})}{n} \log_2 \frac{n_{ij} \cdot n}{n_i \cdot n_j} \quad (1)$$

where the number of correctly recognized patterns is equal to the integer part of  $2^{IT_{est}}$ ,  $k$  is the number of stimulus alternatives,  $n$  is the total number of trials,  $i$  and  $j$  are the indices for stimuli and responses respectively,  $n_{ij}$  is the number of trials when stimulus  $i$  is responded to as  $j$ ,  $n_i$  is the total number of trials that stimulus  $i$  is presented, and  $n_j$  is the total number of trials that the user responds to as  $j$ . Throughout this dissertation, Formula (1) will be used as a summary metric when discussing the perception of tactile patterns.

As a method for non-verbal communication, the study of tactile displays originated from sensory substitution for the deaf and the blind. Researchers have studied the information transfer rate of tactile displays with various stimulation profiles (Table 5).

The design of tactile displays requires broader concerns beyond perception such as appropriate stimulus-to-meaning mappings and training. Although the focus of this dissertation is limited to the perception issue of tactile stimulation, this section briefly covers an overview of existing systems for tactile information transmission to explore various factors that are associated with the design of tactile displays and patterns.

Three types of stimulation profile (described in Table 5) reflect different ways to map stimulus and response: direct mapping, abstract encoding, and perception. Direct mapping and abstract encoding involve sophisticated coupling between perceived stimulation and

**Table 5:** Overview of tactile communication and information transmission

System	Stimulation profile	Sensation parameter	Perception method	Quality of touch	$IT_{est}$
Tadoma	Direct mapping	Active	Two hands	Mouth opening, air flow, vibration muscle tension	12 bits/sec [99]
Optacon	Direct mapping	Active passive	Index finger (Twohands)	Vibration	5.4 bits/sec [21]
Braille	Abstract encoding	Active	Fingers	Texture	9.3 bits/sec [32]
Reverse typewriter	Abstract encoding	Passive	8 fingers	Site, movement (force feedback)	4.5 bits/sec [7]
MIT Morse code display	Abstract encoding	Passive	1 finger	Movement (force feedback)	2.7 bits/sec [116]
Tactuator	Perception	Passive	3 finger	Waveform (frequency, amplitude), site, stimulus length	12 bits/sec [114]

meaningful information whereas perception refers to simple understanding of the tactile stimulation that is delivered through the configuration of various parameters.

#### 2.1.4.1 Direct mapping

Direct mapping refers to the straightforward mapping between a source of stimulus and a coupled meaning. Tadoma is a method for tactual speech communication that is beneficial for users who are both deaf and blind. During speech communication, various tactile signals are generated based on the speaker’s mouth opening, laryngeal vibration, muscle tension around the cheek, and airflow. These rich tactile signals are conveyed by the face and neck of the speaker. This method of speech communication is known to deliver an auditory profile of speech as well as accent with relatively efficient transfer rate (12 bits/sec, [99]).

Optacon (Telesensory Corp, Mountain View, CA) is a vision-to-touch information transfer system that renders the shape of scanned images on a 24x6 array of vibrating pins. While one hand scans black and white images of pictures or letters with a wand equipped with an array of photocells, the index finger of the other hand senses vibrations that correspond to the black spots of the scanned image. Although the tactile rendering on the index finger involves passive touch, active touch with proprioception is partially involved while scanning the image with the other hand. The tactile display fits under the index finger (1.1 cm x 2.7 cm), and the typical information transfer rate is about 5.4 bits/sec [21].

#### 2.1.4.2 *Abstract encoding*

Abstract encoding utilizes a real world metaphor or symbols such as typewriter or Morse code when mapping tactile perception to meaning. This method is known to enhance tactile pattern perception with a small amount of training [23, 37]. One of the most well known abstract tactile encodings is Braille. Braille renders letters, numbers, and punctuation by configuring a bumpy texture of a six dots matrix. The average reading speed of Braille is 9.3 bits/sec with significant individual variation [32].

Reverse Typewriter utilizes a keyboard-based typewriting metaphor when delivering force feedback to the user’s eight fingers. While the user rests his fingers on the home position of the typewriter, the kinesthetic movement of the key provides feedback on the fingers to render corresponding letters. Similarly, the MIT Morse code display employs the Ham radio keyer as a metaphor for communication. Force feedback on the user’s fingertip conveys a variant of Morse code rhythm. The information transfer rate of experienced users of the Reverse Typewriter and the MIT Morse code display is 4.5 bits/sec [7] and 2.7 bits/sec [116], respectively.

#### 2.1.4.3 *Perception displays using minimal mappings to convey information*

The Tactuator [114] transfers information through one degree-of-freedom force feedback using magnitude information transmission [79]. The waveform is designed by varying frequency and amplitude and combining four locations for stimulation (thumb, index finger, middle finger, or all three) and three stimulus durations (500 ms, 250ms, and 125 ms). The average estimated  $IT_{est}$  rate was 12 bits/sec.

## 2.2 *Attentional resources of humans in dual task performance*

This section presents basic human capabilities and limitations in managing attentional resources as well as several experiments that reflect human characteristics in dual task performance.



### 2.2.1 Attentional resources of humans

#### 2.2.1.1 *Attentional paradigms*

Humans perform multiple tasks simultaneously or successively based on their strategy for managing attentional resources. Attentional paradigms of humans are mainly classified as selective, divided, and focused [128]. Selective attention is when humans select a preferred stimuli at the expense of other stimuli. Divided attention is when subjects attend multiple stimuli or tasks simultaneously. Focused attention refers to the ability to reject irrelevant stimuli.

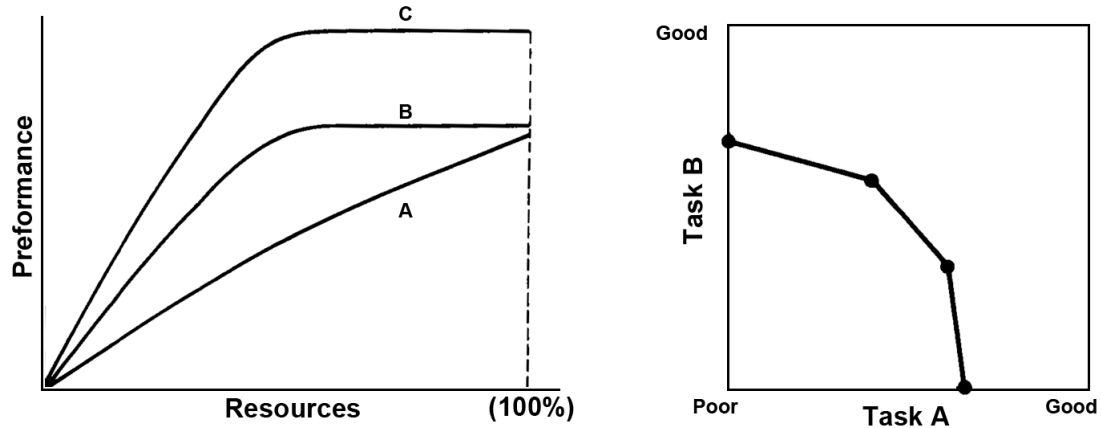
#### 2.2.1.2 *Attentional phenomena*

When multiple stimuli are presented, the decision to select, prioritize, or ignore the stimuli is mostly affected by the consistency and familiarity of the information [105]. For example, consistently mapped (CM) stimuli and response is easier to perceive than variably mapped (VM) stimuli and response. Similarly, a familiar or practiced task (automatic processing) is easier to perform than an unfamiliar task (control processing). In general, the bottleneck of human attention induces the selection of one task at the cost of other stimuli [105] (e.g., missing the red light signal at the intersection while watching the mobile phone) or timesharing of multiple tasks at the cost of inefficiency [128] (e.g., slowing down the driving speed while talking on the phone).

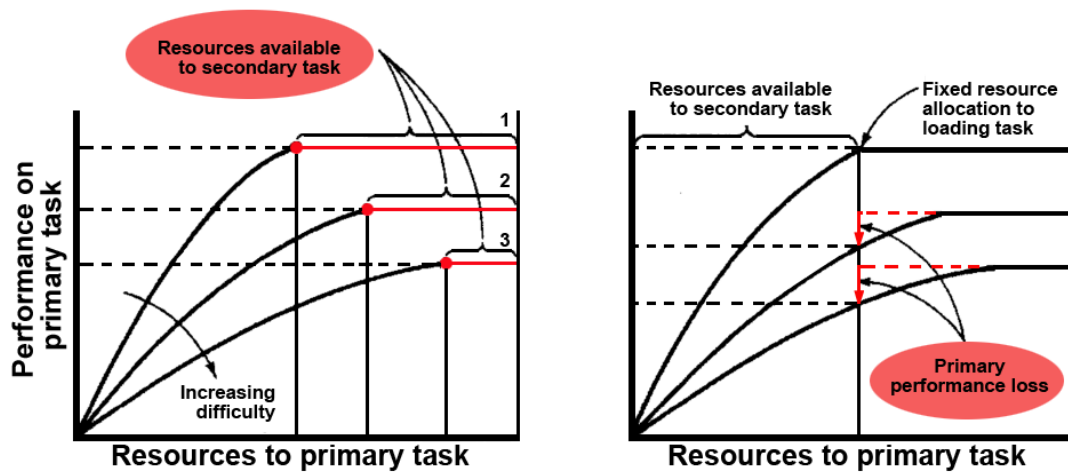
#### 2.2.1.3 *Assessing workload of dual task performance*

Grounded in the assumption of limited capacity of processing resources, the performance-resource function (PRF) [81] hypothetically explains the relationship between human performance and the effort (resources invested), in which the performance is increased by the amount of invested resources. Task difficulty (Figure 9-left) and allocation of resources (Figure 9-right) are two relevant factors that are associated with the PRF in multiple task performance.

In general, whether the user attends single or multiple tasks, performance increases as the task is rehearsed or becomes easier, whereas the performance decreases as the task



**Figure 9:** Processing resources in attention (adapted from Norman and Bobrow [81]): Performance-resource function (PRF) for tasks differing in practice or difficulty: A=difficult, B=easier or practiced, C=easiest (left), Performance operating characteristic (POC) (right).



**Figure 10:** Relationship among the performance-resources function (PRF), resources allocation, and primary task difficulty (adapted from Wickens and Hollands [129]): Secondary-task technique (left), loading-task technique (right).

becomes difficult or unpracticed (Figure 9-left). In particular, when managing two tasks simultaneously, the allocation of resources creates a reciprocal performance tradeoff (Figure 9-right) which is graphed as a performance operation characteristic (POC) [81].

In addition to performance, workload is known as an important qualitative value when assessing the efficiency of the task. Assessment of workload in dual task performance is grounded in the relationship between resource supply and task demand [129]. In association with PRF and POC, management of the resource supply and task demand in the dual task

scenario can be hypothetically explained in two ways (Figure 10) [85, 101]:

- Secondary-task technique: When the subject allocates resources mainly to the primary task, only residual resources can be assigned to the secondary task. As the difficulty of the primary task increases, the remaining resources for the secondary task are reduced (1, 2, and 3 of Figure 10-left). This *secondary-task technique* is useful when examining the variation in performance in the secondary task as compared to when the secondary task is the only task being performed.
- Loading-task technique: When the subject is asked to devote all possible effort to both tasks with no prioritization, the intrusion of the secondary task affects the primary task. As the difficulty of the primary task increases, the task experiences performance loss (Figure 10-right). This *loading-task technique* is useful when the research question examines the decline in performance in the primary task associated with increasing difficulty and interference of the secondary task.

Chapter 5 explores the effect of WTDs in dual task conditions. The hypothesis and study design uses both the secondary-task technique and the loading-task technique.

## 2.2.2 Design of multitasking-friendly mobile UIs

When designing multitasking-friendly mobile UIs, exploring the ability to manage attentional resources is essential to ensure safe and efficient interaction. On-the-go users' performance with mobile devices is affected in many ways. Interaction fluency, frequency of interaction, user confidence, and the user's willingness to interact change from situation to situation. Creating a strategy to prioritize tasks and organize available resources is another task that can distract users. In general, mobile interaction is "cognitively costly" [90]. When the user interacts with mobile devices in the wild, the cognitive resources compete with each other to achieve appropriate organization in mobile computing [75, 90, 103]. In most cases, the users' visual attention is overloaded because the user is required to shift attentional focus frequently from the mobile device to the surroundings.

A group of experimental psychologists compared the performance of single and dual

**Table 6:** Modality and types of multitasking

Properties	Rubinstein et al.[102]	Schmacher et al. [106]
S-R (stimulus-responses) for dual task	Visual-Motor Visual-Motor	Auditory-Vocal Visual-Manual
Multitasking process	Sequential	Parallel
Organization of attention	Attention shifting	Attention sharing
Reaction time performance	Delay	No delay

tasks using visual stimuli and manual (hand) responses. The study revealed that frequently shifting visual attention causes more difficulty during dual stimulus-response (S-R) tasks than during single S-R tasks [102]. On the other hand, another group of studies suggests that users can concurrently process dual S-R tasks when modalities are different (e.g., auditory-vocal and visual-manual). In this case, the performance of dual S-R tasks is as fast as single S-R tasks after a certain amount of practice [106]. By comparing the results of these two studies (Table 6), a hypothesis regarding mobile multitasking can be constructed:

- When the modalities overlap in two S-R tasks, the user may either prioritize one task at the cost of the task shifting (selective attention) or simultaneously perform two tasks at the cost of inefficiency (divided attention).
- When the modalities do not overlap in two S-R tasks, the cost of selective attention (task shifting) and divided attention (inefficiency) may be significantly reduced.

Based on this hypothesis, I have selected the sense of touch as an appropriate modality for mobile interfaces. The visual modality is often needed by the user for observing his environment (primary task) and is not always available for mobile computing tasks (secondary task). For example, a study that compared a reading comprehension task using visual and audio displays while walking showed that the audio display enables better reading performance, lower workload, and higher ability to navigate the environment [120]. Compared to sitting, walking required more visual attention to navigate the environment, which led to slower reading speeds and lower comprehension scores [4, 5].

## CHAPTER III

### DESIGN OF WEARABLE TACTILE DISPLAYS AND TACTILE PATTERNS

This chapter discusses the design of WTDs on a wristband and the limitations on which stimuli are perceptible using two-dimensional arrays.<sup>1</sup> The first half of the chapter presents the design iteration process. The rest of the chapter explores the finalized design of the tactile display and the patterns to be evaluated in the subsequent chapters.

#### *3.1 Overview of design iteration*

I developed my WTDs and tactile patterns through three phases of iteration (Table 7): an electro-tactile display using a 4x4 grid to produce 18 patterns, a vibro-tactile display using a 4x4 grid to generate 12 patterns, and a vibro-tactile display using 3-points to generate 24 patterns.

**Table 7:** Three phases of design iteration

Phase of Iteration	Display Type	Actuators layout	Tactile Patterns
1 (Figure 11)	Electro-tactile display	4x4 grid	18 patterns
2 (Figure 18)	Vibro-tactile display	4x4 grid	12 patterns
3 (Figure 26)	Vibro-tactile display	3 points in inverted triangular layout	24 patterns

#### *3.2 Phase 1: Electro-tactile displays*

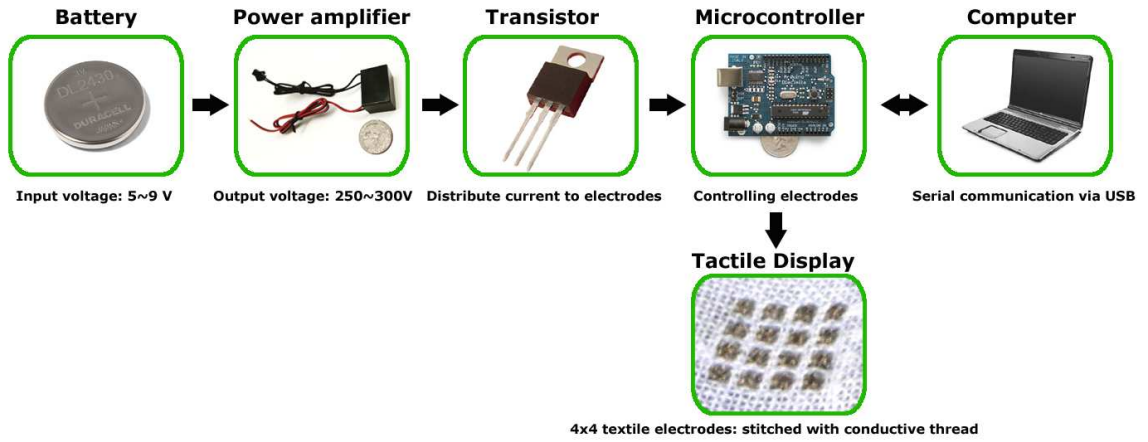
First, I began with electro-tactile displays that utilize the electro conductivity of human skin. Lessons and challenges learned from a pilot test are presented in this section.

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<sup>1</sup>Parts of this chapter have been published in the IEEE International Symposium on Wearable Computers (ISWC) [68] and SIGCHI Conference on Human Factors in Computing Systems (CHI) [67, 69].



**Figure 11:** Hardware design Phase 1: Electro-tactile display with 4x4 grid.

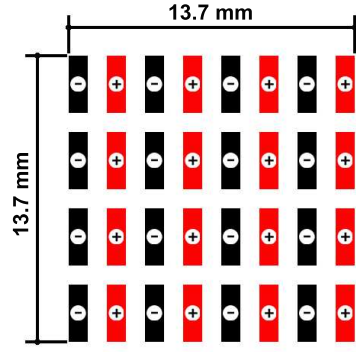


**Figure 12:** Hardware system diagram for Phase 1 (electro-tactile displays).

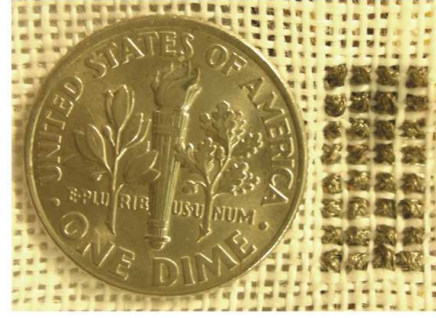
### 3.2.1 Design of electro-tactile displays

The electro-tactile display was implemented with a grid of textile electrodes. A voltage multiplier (1" x 0.5" x 0.25") for the electro-tactile display was powered by 5-9V batteries and generated 250VDC, fully rectified (Figure 12). A transistor was used to buffer the microcontroller from the high voltage, and the microcontroller controlled which electrodes were energized at a given time. The grid of electrodes was cross-stitched with conductive thread and connected to an elastic wristband (Figure 11). Figure 13 shows the evolution of the design of the electro-tactile display.

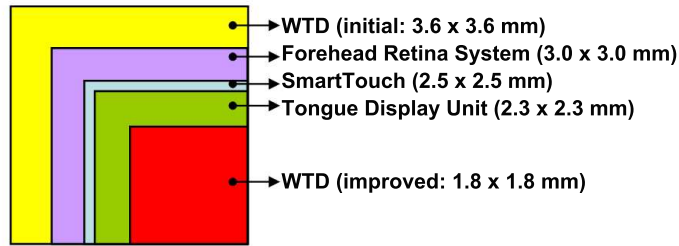
In the initial display design [68], a pair of electrodes functioned as a single pixel (Figure 13-A). A half-bridge switch [62] was used to create an improved display where one electrode



**A. Initial Design**  
(3.6mm x 3.6mm per pixel)



**B. Improved Design**  
(1.8mm x 1.8mm per pixel)



**C. Pixel size comparison:**  
**WTD and other electro-tactile displays (mm x mm)**

**Figure 13:** Design iteration and resolution for wearable electro-tactile display: A (Initial design), B (Improved design), C (Size comparison of initial and improved design with Tongue Display Unit [3], SmartTouch [63], and Forehead Retina System [62]).

mapped to each pixel (Figure 13-B). The improved display allowed higher resolution and simplified the hardware implementation. With this improvement, the display can contain up to 14 x 14 pixels in 1 inch square when stitched on a piece of 28 count Aida cloth, which has 784 (28 x 28) holes per square inch. At this resolution, the size of each electrode is 0.9mm x 0.9mm, and the center-to-center distance between each pixel is 1.8mm x 1.8mm. The respective sizes of the completed displays in comparison with other studies can be seen in Figure 13-C [3, 62, 63]. Note that the two point discrimination threshold (TPDT) for the fingertip is 4mm for most people and 2mm for people with very sensitive perception of touch [49]. It is assumed that the resolution of this display is higher than human perception on the wrist.

### 3.2.2 Design of eighteen tactile patterns and pilot testing

While creating the electro-tactile display, I also tested candidate directional tactile patterns. By utilizing 16 points in the 4x4 grid, one or multiple points were activated and deactivated sequentially to generate a tactile illusion of motion. The initial set of tactile patterns is illustrated in Figure 14. The duration of all patterns is set to four seconds. In previous research, four seconds was measured as the average time users will focus on a mobile phone display while navigating a busy street [90] — an example of distracted mobile device use in the wild. Thus, I use four seconds as a guideline for creating tactile alerts.

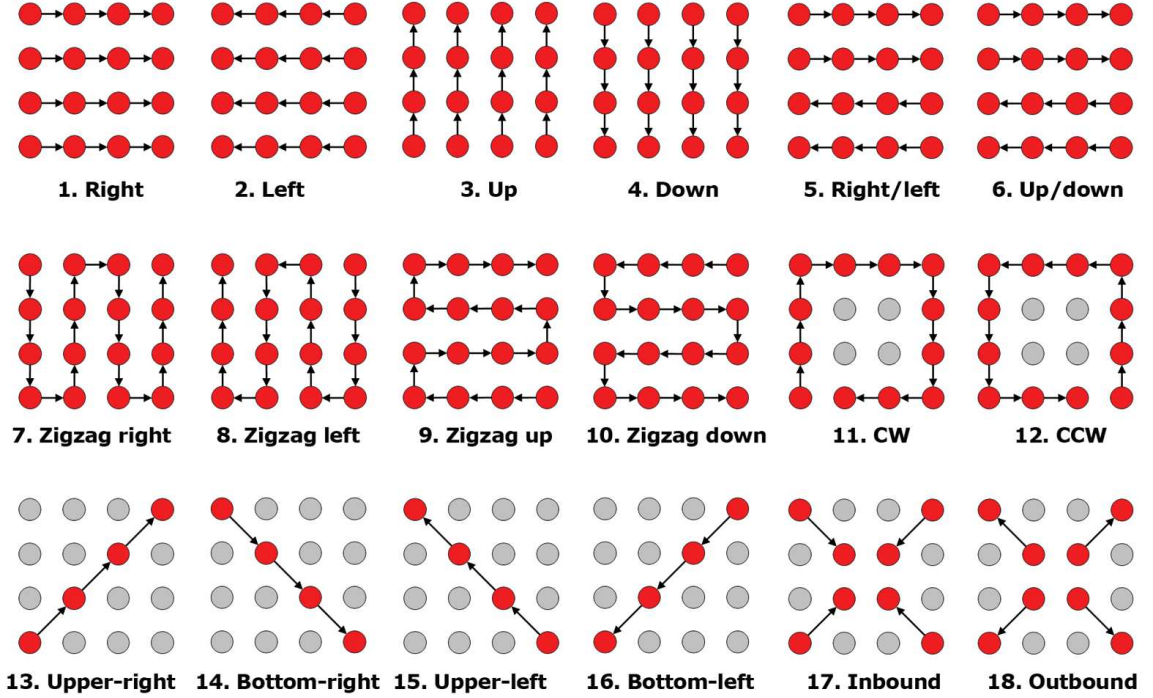
Given the limitation of four seconds, each tactile pattern has a different temporal profile defined by the number of steps needed to form the shape and movement of the pattern. The number of steps ranges from two (patterns 17 and 18 of Figure 14) to 16 (patterns 7, 8, 9, and 10 of Figure 14). For example, in pattern 18, which is designed to generate a tactile pattern that moves outward from the center, four points at the center of the grid are generated simultaneously during the first step for about two seconds. At the second step, these four points are deactivated, and four points at the corner of the grid are activated simultaneously for about two seconds. The temporal pattern is illustrated in Figure 15-A.

The perception of these patterns was tested informally with the initial electro-tactile display (Figure 13-A). The size of the 4x4 grid is 13.7mm x 13.7mm. Center-to-center distance between pixels is 3.6mm x 3.6mm. The display was worn on the volar (same side as palm) side of the wrist because the hairy surface of the dorsal (back) side of the wrist might cause a decrease in electric conductivity. Two subjects participated in three experiments during the pilot study and gave feedback verbally.

#### 3.2.2.1 *Experiment 1: What is the appropriate speed and number of steps to generate directional tactile patterns that are easy to perceive?*

In this experiment, each pattern in Figure 14 was generated in numerical order. To achieve a total duration of four seconds, the patterns' speeds were adjusted depending on their total number of steps. Figure 15 illustrates the number of steps and duration for each pattern. A sense of direction was stronger in patterns with four steps (Figure 15-B) than those with



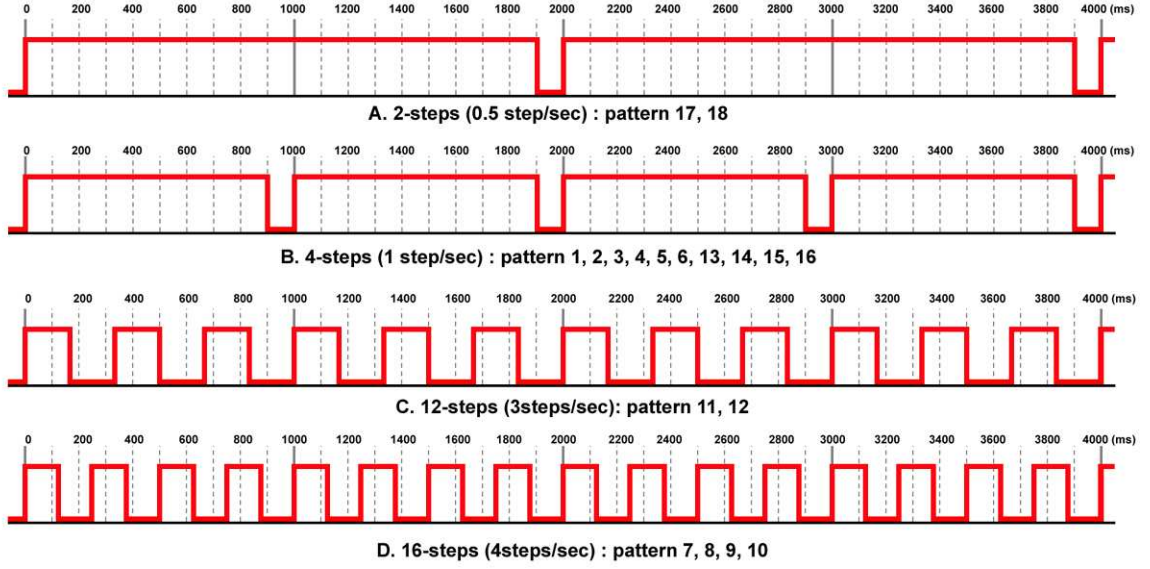


**Figure 14:** Directional tactile patterns of Phase 1.

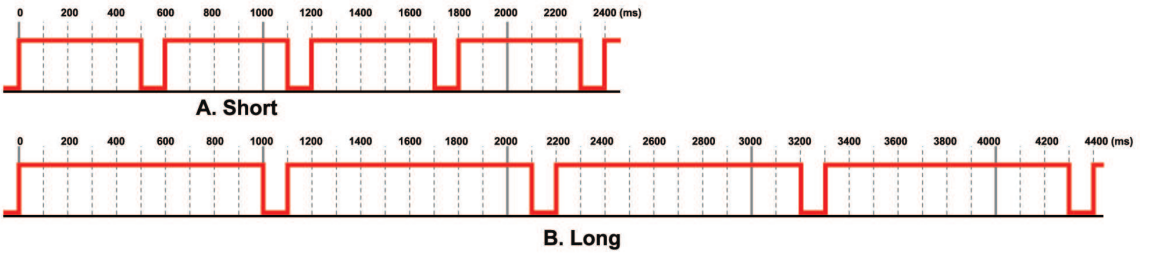
two steps (Figure 15-A). Participants reported that two steps are too short to perceive the movement of the changing direction. I expected that using longer sequences would eliminate this problem. However, patterns with 12 steps (Stimulus duration = ISI = 166ms, Figure 15-C) and 16 steps (Stimulus duration = ISI = 125ms, Figure 15-D) did not produce better results because the movement speed is too fast.

### 3.2.2.2 Experiment 2: What is an appropriate combination of stimulus duration and inter-stimuli-interval (ISI)?

Based on the findings from the previous experiment, four patterns (patterns 1, 2, 3, and 4 in Figure 14) with four steps were selected for testing in this experiment. Two types of stimulus length, short (500ms) and long (1000ms), are provided. The ISI between the stimuli is set to 100ms. In this configuration, the total durations for the short and the long patterns are 2.4 seconds and 4.4 seconds, respectively, including the ISI. 500ms long stimuli (Figure 16-A) were more distinct than 1000ms long stimuli (Figure 16-B). Participants reported that the 1000ms long stimulus required too long a time to concentrate to catch the moment that the locus of the stimulus moved.



**Figure 15:** Experiment 1 in Phase 1 pilot study: Temporal patterns.

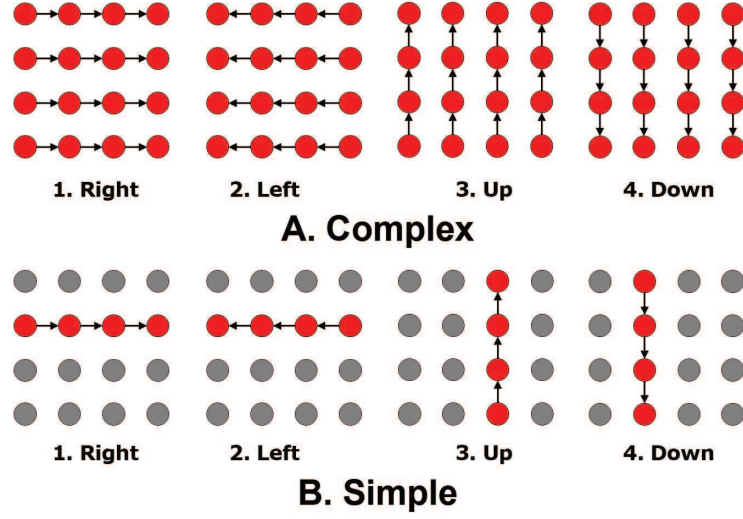


**Figure 16:** Experiment 2 in Phase 1 pilot study: Stimulus length.

### 3.2.2.3 Experiment 3: What is the appropriate strategy to utilize the 16 points in the 4x4 grid?

Based on the findings of two previous experiments, four patterns (patterns 1, 2, 3, and 4 in Figure 14) with four steps are tested in this experiment. The temporal pattern is set as shown in Figure 16-A. It has a 500ms stimulus length and a 100ms ISI. In this experiment, each pattern is configured in two ways: complex (Figure 17-A) and simple (Figure 17-B). The complex pattern utilizes all possible pixels in the display (maximum use) whereas the simple pattern utilizes only one row or column in the display (minimum use).

Participants reported that the directional patterns were more distinguishable when a single column or row was used (Figure 17-B). Patterns that utilized all columns or rows (Figure 17-A) caused confusion. I hypothesize that the confusion occurred for two reasons.

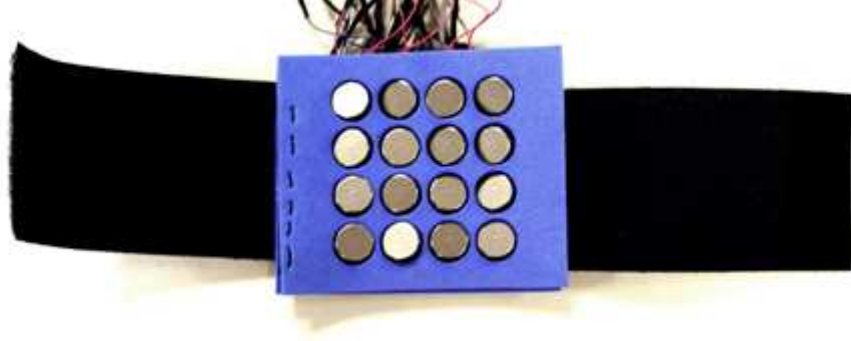


**Figure 17:** Experiment 3 in Phase 1 pilot study: Complexity.

First, the TPDT for simultaneously activated points can be larger than the TPDT for successively activated points. Second, since the amount of current applied to each electrode is determined by the number of activated electrodes, the intensity of the tactile sensation might be different for complex patterns (maximum use of the display) versus the simple patterns (minimum use of the display). For further study, a system should be designed that assigns the same amount of current for each electrode.

### ***3.3 Phase 2: Vibro-tactile displays with 4x4 grid***

For Phase 2, I changed from electro-tactile displays to vibro-tactile displays for two reasons. First, the problems with ergonomics and electro-cutaneous perception that were observed in the Phase 1 pilot test are difficult to overcome. During the pilot study of Phase 1, the participants reported that perception is highly affected by the tightness of the strap. When the strap is too tight, the sensation is sometimes perceived as irritating and itchy. On the other hand, when the strap is too loose and fails to provide appropriate contact between the skin and the electrodes, the sensation is hard to perceive. Since large amounts of physical activity are expected in on-the-go situations, this issue is a serious challenge in designing electro-tactile displays. Although applying conductive gel helps to reduce skin irritation



**Figure 18:** Hardware design Phase 2: 4x4 vibro-tactile display.

caused by electro-tactile stimulation, the feeling of the tactile sensation was not fully controllable by the time the pilot test was conducted. Thus, a vibro-tactile display was designed and tested for the pilot test while the electro-tactile display was improved. The problem with the electro-tactile display might be solved by applying a thin layer of conductive gel (shipped commercially with Transcutaneous Electrical Nerve Stimulator (TENS) units) between the textile electrodes and the skin. A second reason for switching to commercial vibrating motors is that the resulting vibro-tactile display was more stable than my custom-made electro-tactile display by the time the pilot test was conducted.

### 3.3.1 Design of a 4x4 vibro-tactile display

For my vibro-tactile display, I inserted flat button-shaped shaftless vibrating motors (Precision Microdrives #301-101, 200Hz,  $d = 10\text{mm}$ ,  $h = 3.4\text{mm}$ ) into holes in soft plastic foam (Figure 18). The foam was attached to an elastic wristband. The motors were controlled by a microcontroller which was connected to a computer (Figure 19). The diameter for the holes in the foam was slightly larger (11mm) than the size of the motors to ensure clearly isolated vibration of each motor while correctly placing the motor in its designated location. The size of the 4x4 grid is approximately 60mm x 60mm and the center-to-center distance between each motor is 13mm. The resolution of the vibro-tactile display is 1.69 x 1.69 pixels per square inch.

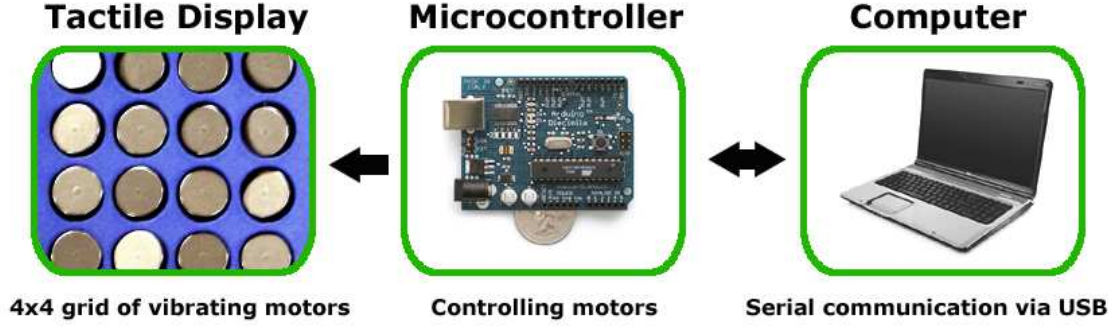


Figure 19: Hardware system diagram for Phase 2 (vibro-tactile displays).

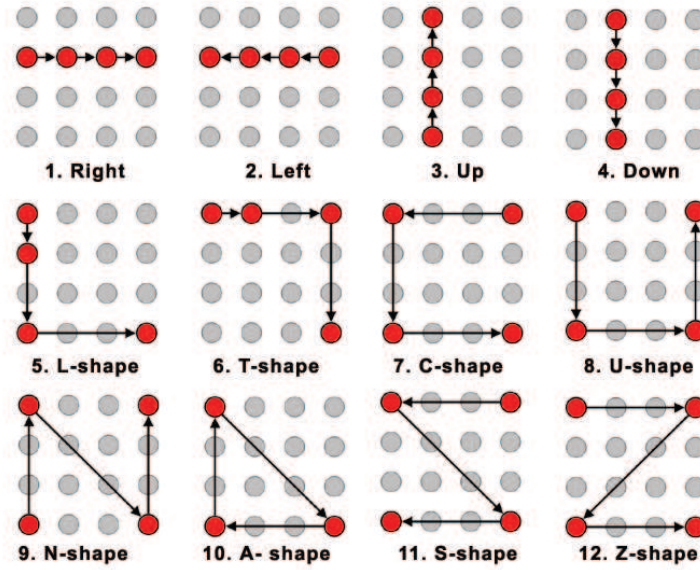


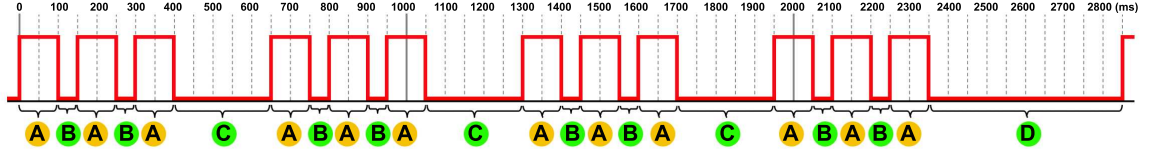
Figure 20: Directional tactile patterns of Phase 2.

### 3.3.2 Design of twelve tactile patterns using directional mnemonics

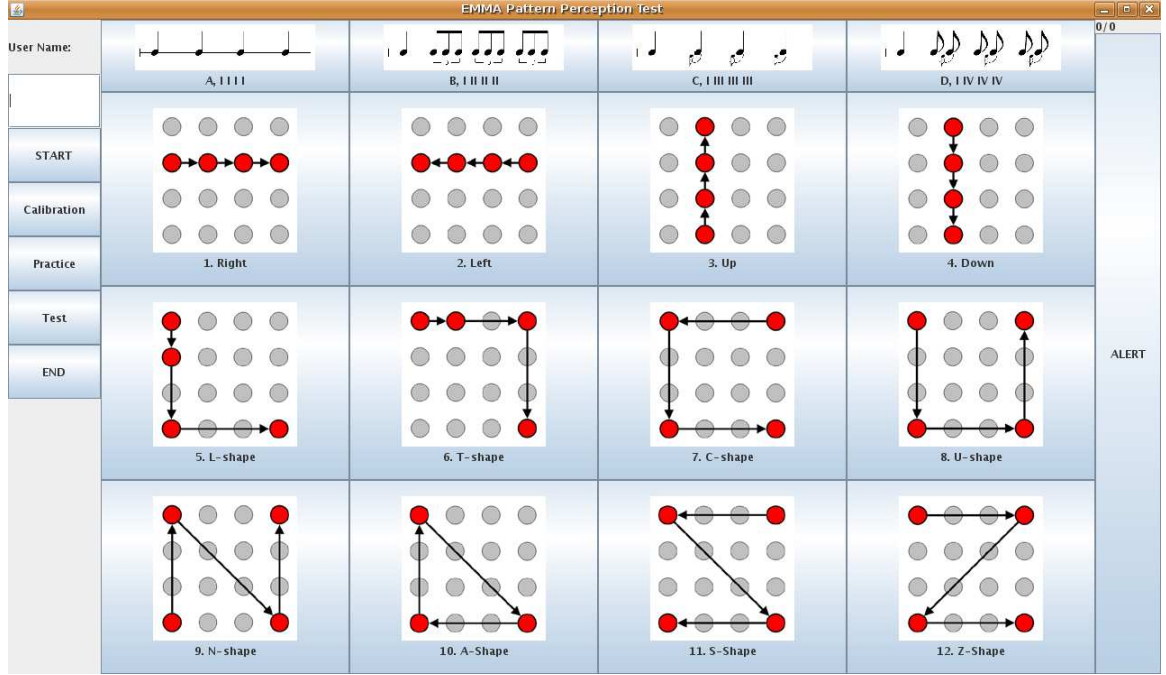
Based on observations from the previous pilot test, I designed a new set of patterns as shown in Figure 20. In this set of patterns, the number of steps, speed, and total duration are consistent (Figure 21). The twelve patterns in this new set are 4 steps long. Only one pixel is activated at a time, which means that four pixels are activated in total to generate the four step pattern.

Since the perception of tactile patterns is affected by repetition and ISI [18, 39, 40], I repeat the pattern three times at each locus to take advantage of a temporal summation





**Figure 21:** Temporal pattern for the directional tactile patterns in Phase 2: 100ms-long unit sensation (A), 50ms-long intra-step interval (B), 250ms-long inter-step interval (C), 550ms-long loop-segmentation interval (D).



**Figure 22:** Pilot test GUI screenshot for Phase 2.

effect (Figure 8-right). Figure 21 demonstrates the patterns used. Each vibrator is turned on for 100ms (Figure 21-A). The intra-step interval in a locus (Figure 21-B), inter-step interval between loci (Figure 21-C), and delay before the whole pattern is repeated (Figure 21-D) are 50ms, 250ms, and 500ms, respectively. Thus, the total duration for each loop was 2.85 sec.

Given this temporal pattern, four patterns drew horizontal or vertical lines (1, 2, 3, and 4 of Figure 20) and eight patterns drew a shape resembling a letter by utilizing the outer boundary of the display (5, 6, 7, 8, 9, 10, 11, and 12 of Figure 20).

### 3.3.3 Pilot test

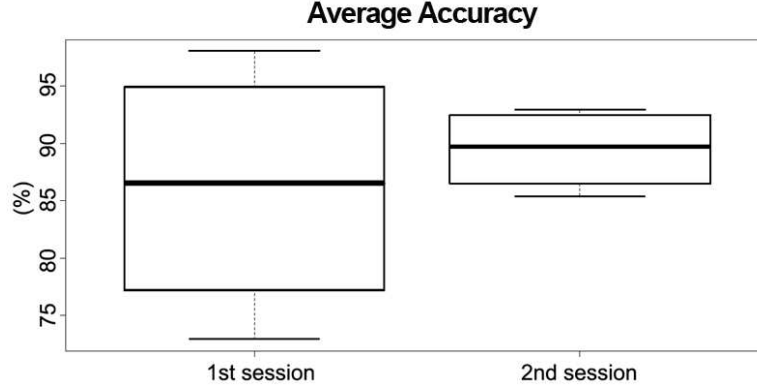
I conducted a pilot study with four participants testing users' accuracies in perceiving the 12 tactile patterns (Figure 20) and collected 384 trials of data. All participants were male and right-handed. Participants were asked to wear the tactile display on the left wrist (non-dominant hand). The system was installed on a desktop computer and the experiment was performed in a quiet room.

A graphical user interface (GUI) assisted the participants during the test (Figure 22). When the participant clicked on the 'alert' button on the right side of the testing GUI, the tactile pattern was generated on the wrist-mounted tactile display. The pattern was repeated until the participant recognized the pattern and clicked on the corresponding button on the testing GUI. Each directional pattern matched a corresponding button on the testing GUI which was labeled with the pattern's name and an icon visualizing the pattern.

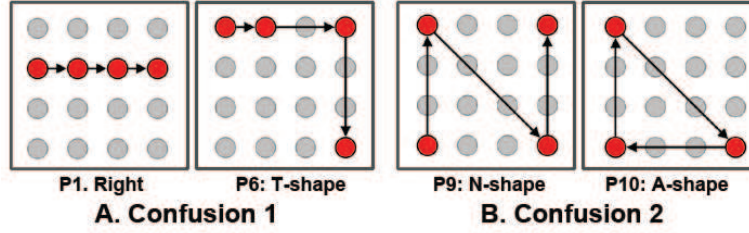
The pilot test was composed of a preliminary session, practice session, two main sessions (first and second) and post session. During the preliminary session, demographic data including the width and circumference of the subject's wrist was collected. The participants then had the practice session. In the practice session, the directional patterns were generated on the wristband in order from 1 to 12 as labeled in Figure 22. During the first and second main sessions, each pattern was generated four times in randomized order (12 patterns x 4 repetitions x 2 sessions = 96 trials/participant). A five minute break was enforced between sessions.

The average width and circumference of the wrist was 56.6mm (SD=2.35) and 162mm (SD=2.5), respectively. Note that the size of the vibro-tactile display was 60mm x 60mm, and the pixels on the leftmost and rightmost columns on the display would be placed slightly on the side of the wrist rather than the volar side of the wrist.

The average accuracy for the first and second session was 85.98% (SD=11.10) and 89.45% (SD=3.58), respectively (Figure 23). The confusion matrix indicates that 38% of the errors were between two pairs of patterns: P1-P6 and P9-P10 (Figure 25). By excluding these two pairs of patterns from the analysis, the accuracy rate for first and second session increased



**Figure 23:** Pilot test result (accuracy).



**Figure 24:** Two main types of confusion in Phase 2.

slightly to 86.72% (SD=11.79) and 91.41% (SD=9.35), respectively.

The confusion between the P1-P6 (Figure 24, A) and P9-P10 (Figure 24, B) seems to be due to the patterns being identical from step 1 to step 3. That is, the directional patterns of P1 and P6 is similar except for the fourth step. Although the spatial distance between step 2 and step 3 is different in P1 and P6, it does not provide a distinctive cue for recognition. As such, the directional pattern of P9 and P10 are very similar except for the fourth step. Although these patterns are labeled with the alphabetical mnemonic, it does not assist perception very much. Participants reported that the closing loop of P10 was confusing. It seems that even though the pause between the pattern's repetition is longer than the inter-step interval (Figure 21-D), having the sensation on the same spot for the first step and the fourth step can cause serious confusion.

During the post session, participants reported their subjective opinions. One participant reported that he used the two vibrators mounted over the wrist bone (leftmost and rightmost



All		Q												false alarm
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	
A	P1	23			1	1	5		2					9
	P2		27											
	P3			30										
	P4				30	2					1			3
	P5				1	28		2	2			1		6
	P6	7					25			1				8
	P7							27						
	P8								25	1				1
	P9	1							2	29	10			13
	P10		2	2					1		21	1		6
	P11		3					2		1		31	1	7
	P12	1				1	2	1					30	5
miss		9	5	2	2	4	7	5	7	3	11	1	2	

**A. All sessions (1st + 2nd)**

1st		Q												false alarm
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	
A	P1	13			1	1	3							5
	P2		13											
	P3			14										
	P4				15	2								
	P5					13		1	1					2
	P6	3					13							3
	P7							12						
	P8								13					
	P9							1	16	5				6
	P10			2					1		11	1		4
	P11		3					2				15		5
	P12							1					16	1
miss		3	3	2	1	3	3	4	3		5	1		

2nd		Q												false alarm
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	
A	P1	10					2		2					4
	P2		14											
	P3			16										
	P4				15						1			1
	P5				1	15		1	1				1	4
	P6	4					12			1				5
	P7							15						
	P8								12	1				1
	P9	1							1	13	5			4
	P10		2								10			1
	P11									1		16	1	2
	P12	1				1	2						14	4
miss		6	2		1	1	4	1	4	3	6		2	

**B. 1st session**

**C. 2nd session**

**Figure 25:** Confusion matrix for the pilot test data for Phase 2.

point on the top row) as an anchor to recognize the patterns because these points delivered stronger sensation than any of the other points. However, it is unclear whether the magnified intensity is due to bone conduction or coupling to the nerve fiber that is close to the wrist at that point (Figure 5, [44]).

### 3.4 Phase 3: Vibro-tactile display with three actuators

The high accuracies observed during the Phase 2 pilot study were encouraging. Phase 3 of our prototyping establishes the final design of the WTD that is evaluated formally in later chapters.



**Figure 26:** Hardware design Phase 3: Vibro-tactile display with three actuators in a triangular layout.

### 3.4.1 Design of a 3-point vibro-tactile display

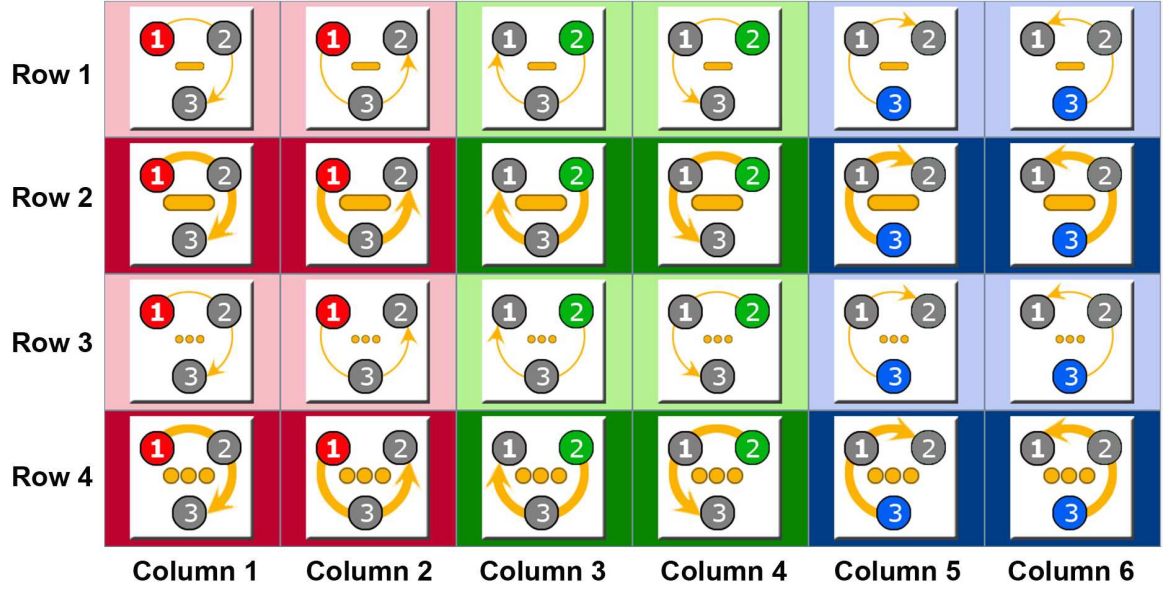
Based on the pilot studies and recent research by Chen et al. [16] that explored the placement of tactors on the wrist, I designed a WTD with three actuators in an inverted triangular layout (Figure 26). Based on this design, I created 24 directional tactile patterns (Figure 27) for further studies.

To implement the WTD, thin button-shaped shaftless vibrating motors (Precision Microdrives #301-101,  $d = 10\text{mm}$ ,  $h = 3.4\text{mm}$ ) are loosely connected to a piece of fabric, which is attached to an elastic wrist band. This wrist band is attached to the wrist by a velcro strap on the volar side (same side as the palm) of the wrist. The center-to-center distance between actuators is 30mm.

### 3.4.2 Design of 24 tactile patterns varying four parameters

I designed 24 directional tactile patterns manipulating four parameters: starting point (motors 1, 2, and 3), direction (clockwise and counterclockwise), rhythm (steady or pulsed), and intensity (weak or strong). Figure 27 demonstrates these patterns. The pattern is repeated on the wrist until the participants respond with the mouse or keypad. The start-to-start duration for each pattern is 2.25 seconds, including the interval between repetitions (Figure 28).

Design of the testing GUI (Figure 27) focused on creating an efficient visualization for the icon for each pattern so that the participants could match the perceived parameters between what they felt on the skin versus what they see on the screen. In the testing GUI,

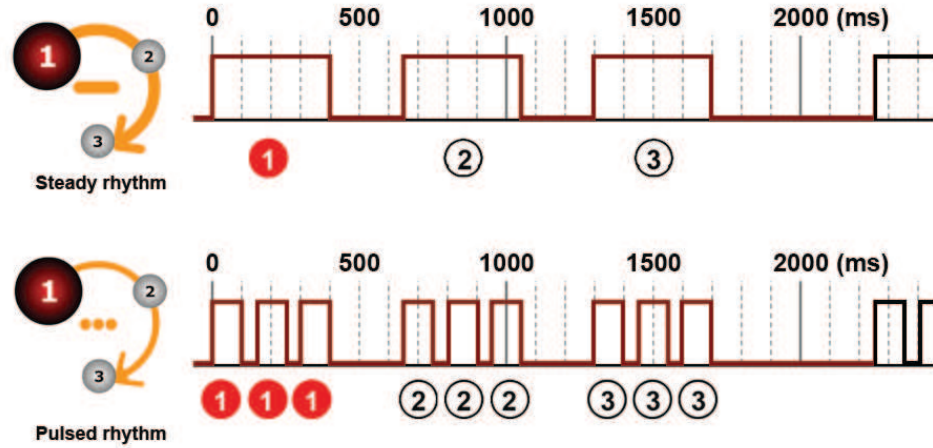


**Figure 27:** Design of directional tactile pattern in Phase 3: : Intensity (Weak: Row 1,3, Strong: Row 2,4), Rhythm (Steady: Row 1,2, Pulse: Row 3,4), Direction (CW: Column 1,3,5, CCW: Column 2,4,6), Starting point (One: Column 1,2, Two: Column 3,4, Three: Column 5,6).

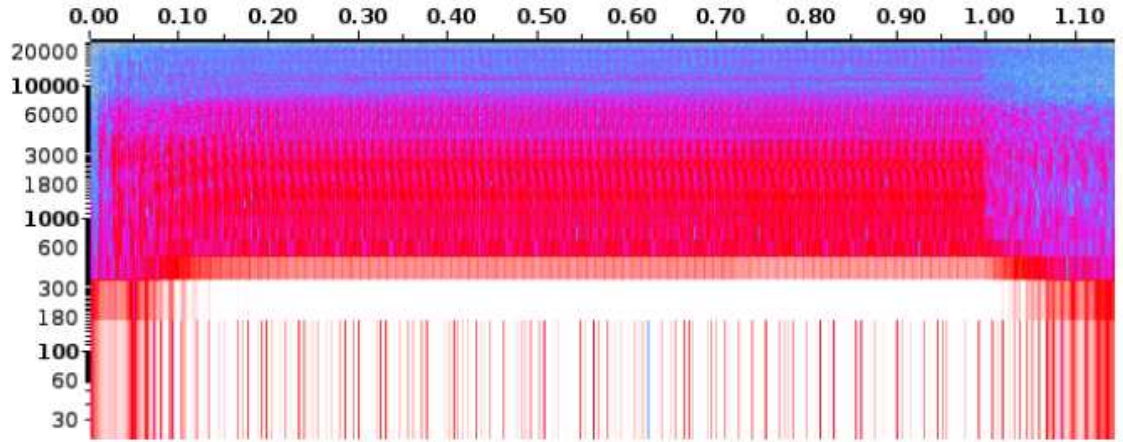
starting point (red, green, and blue for points 1, 2, and 3) and intensity (dark color for strong intensity and pale color for weak intensity) are color-coded, and direction (arrow) and rhythm (dash for steady tempo and dots for pulse tempo) are visualized with corresponding symbols.

Since the motor used in the system (Precision Microdrives, #301-101) requires at least 120 ms to change from full amplitude to full rest (Figure 29), the stimulus duration in a single locus (400ms) and the interval that the tactile stimulus moves from one locus to the other (250ms) is set to be longer than 120ms (Figure 28). The intensity for strong and weak patterns is 0.71g and 0.43g, respectively. The intensity of the strong pattern was set by the maximum strength of the hardware, whereas the intensity for the weak pattern was empirically determined through a pilot test.

Through a pilot test with three participants, the intensity for the weak patterns was selected as the minimum threshold to discriminate between incoming patterns. Since the intensity of the vibrating motors is changed by voltage, the input voltage of the system was



**Figure 28:** Example of rhythm in Phase 3: A pattern that starts from 1 and moves in a clockwise direction with strong intensity and a steady rhythm (Left) A pattern that starts from 1 and moves in a clockwise direction with a weak and pulsed rhythm (Right).



**Figure 29:** Spectrogram generated from a microphone attached to one of the vibrators. The power to the vibrator was started at  $t=0$  and stopped at  $t=1$ .

gradually increased from zero to find the minimum threshold at which people can clearly distinguish incoming tactile patterns.

### 3.5 Summary of the chapter

The design of the WTD and tactile patterns were finalized through three phases of design iteration. User perception of the 24 patterns on the 3-point WTD will be evaluated in the next chapter.

## CHAPTER IV

### TACTILE ALERT PERCEPTION WITH MULTIPLE PARAMETERS WITH THE 3-POINT TACTILE DISPLAY ON THE WRIST

This chapter presents an experiment that explores users' perception sensitivity and reaction time in discriminating multiple parameters (i.e., intensity, direction, starting point, and rhythm) for tactile patterns generated on wrist-worn WTDs.<sup>1</sup> Table 8 shows the goal and overview of the study.

#### 4.1 *Research questions and hypothesis*

This study is designed to explore Research Question 1 and the following subquestions:

**Research Question 1 :** Can a WTD on the wrist be an appropriate interface to present tactile stimuli?

1. With less than an hour of training, can people successfully detect tactile patterns on the wrist?
2. Can people differentiate multiple parameters of tactile sensation simultaneously?

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<sup>1</sup>Parts of this chapter have been published in the SIGCHI Conference on Human Factors in Computing Systems (CHI) [67].

**Table 8:** Overview of the study performed in Chapter 4

Research Question	Hypothesis	Method	Data Collected	Analysis
Research Question 1 subpart: A. Are tactile displays appropriate to deliver easy-to-perceive attentional and directional cues on the wrist? B. Can people easily differentiate multiple parameters of tactile sensation simultaneously?	I hypothesize that wrist-mounted WTDs are appropriate to deliver tactile patterns.	Adults participate while in controlled settings (within-subject). Participants are asked to discriminate four parameters simultaneously to perceive 24 tactile patterns on the wrist. Each pattern is generated through eight sets of repetitions to explore the learning curve.	1. Speed and accuracy of alert perception (quantitative). 2. Learning curve (quantitative). 3. Difficulties in perceiving each parameter in tactile patterns (quantitative, qualitative).	1. Exploring the accuracy and reaction time of novice users in perceiving 24 patterns. 2. Exploring difficulties in discriminating four parameters presented in each pattern. 3. Exploring learning effect. 4. Assessing user-constructed strategies.

The first subquestion explores users’ overall accuracies and reaction time when perceiving incoming tactile patterns. The second subquestion explores the difficulty and strategies utilized by subjects when perceiving multiple parameters encoded in the tactile alerts. The hypotheses of these two subquestions are listed as follows:

**Hypothesis :** I hypothesize that wrist-mounted WTDs are appropriate to deliver tactile patterns.

1. WTDs are appropriate to deliver attentional and directional cues on the wrist.
2. People can differentiate multiple parameters of tactile sensation to decode patterns.

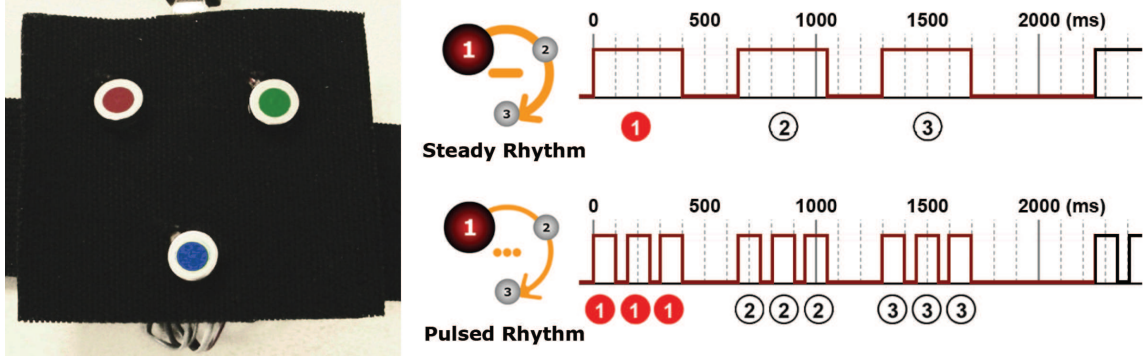
However, as indicated by previous research [10, 36], the perception of intensity may be harder than the perception of other parameters.

#### ***4.2 Study setting***

The study is performed in a quiet lab setting. 17 participants (3 female, 14 male, mean age 29) are recruited from the Georgia Institute of Technology and the Electronics and Telecommunication Research Institute (ETRI). Participants use a laptop computer sitting on a desk and wear the WTD on the wrist of their non-dominant hand. During the experiment, participants are asked to put their non-dominant hand on the desk while facing the volar side of the wrist downwards on top of the desk. With the dominant hand, participants control the mouse to cue the patterns and respond to the incoming alerts. To avoid possible audio cues generated from the motors, participants wear ear plugs and headphones. The three main dependent variables for quantitative analysis are accuracy, reaction time and information transfer ( $IT_{est}$ ).

#### ***4.3 Software and equipment***

The WTD (Figure 30-left) is controlled by a Wiring <sup>TM</sup> microcontroller which is connected to a laptop computer. Software written in Java displays a testing interface (Figure 31) and collects log data with time stamps.



**Figure 30:** A wrist-mounted tactile display with three vibrating motors (left). A tactile pattern that starts at 1 and moves in the clockwise (CW) direction with strong intensity and steady vibration (right-top). A pattern that starts at 1 and moves in the CW direction with weak intensity and pulsed vibration (right-bottom).

**Table 9:** Test procedure

	Introduction	Practice	Main Test	Post
Task & trials	24 × 1 set = 24 trials (numeric order)	24 × 3 sets = 72 trials (random order)	24 × 5 sets = 120 trials (random order)	Survey, interview

#### 4.4 Task and apparatus

The purpose of this experiment is to explore people’s perception of directional tactile patterns on the wrist. The testing GUI (Figure 31) is displayed on the laptop computer to guide the overall procedure with two types of button: an alert button and pattern icons. A 2.25 second pattern (Figure 30-right) with four parameters is generated when the participant presses the alert button at the bottom of the testing GUI. The pattern is repeated until the participant discriminates the characteristics of each parameter and responds by pressing one of the 24 icons on the screen. The next pattern is generated when the participant presses the alert button again.

#### 4.5 Procedure

The experimental procedure is divided into introduction, practice, and main session (Table 9). A minimum five minute break is enforced between sessions to avoid skin adaptation and fatigue.







visual selection on the testing interface, and clicking on the correct button with the mouse. The number of trials in the practice session is 72 (three sets  $\times$  24 patterns). Between each trial, participants are encouraged to take enough break time to avoid an adaptation effect that may decrease perception sensitivity. Additionally, the comfort and tightness of the wristband is adjusted between trials if required.

In the main session, 120 patterns were generated in random order (five sets  $\times$  24 patterns). Between trials, taking breaks is encouraged. However, the adjustment of the wristband is not encouraged unless the misalignment of the wristband causes serious difficulty in perceiving the pattern.

During the practice and the main session, the accuracy and reaction time to discriminate incoming alerts were measured. After completing the main session, participants are asked to complete a survey to report their subjective rating of difficulty for each parameter. A semi-structured interview follows to assess participants' strategies in detecting the patterns, their preferences, and additional opinions.

## **4.6 Results**

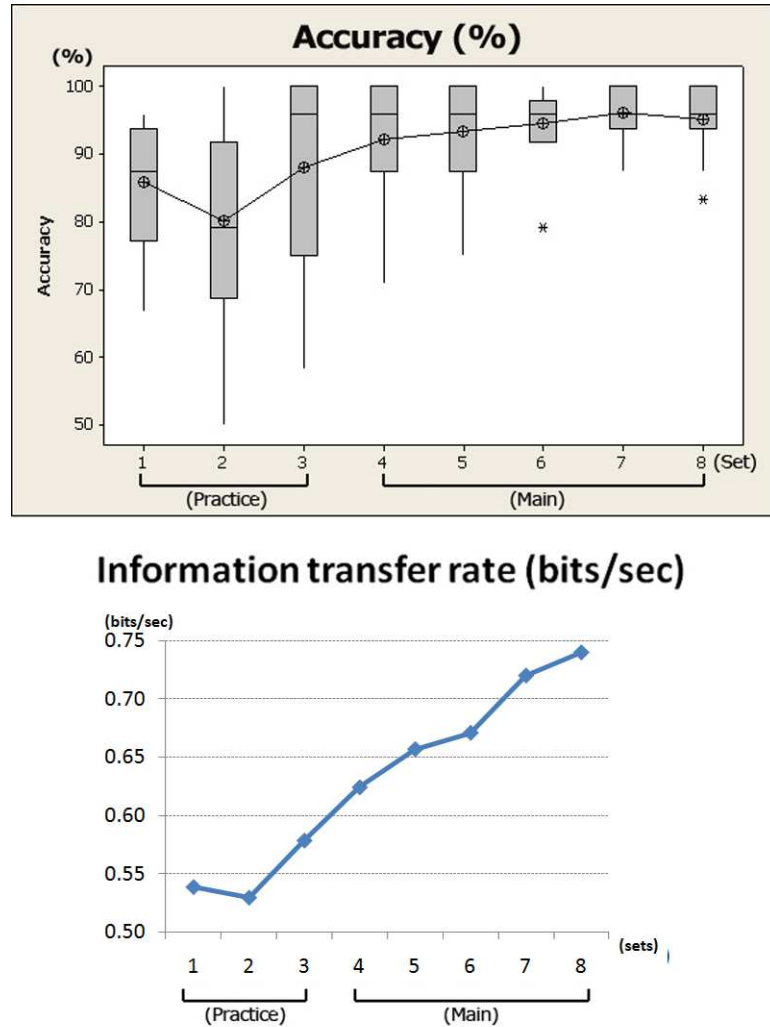
The test was held in a quiet lab setting in the campus of Georgia Institute of Technology and ETRI for about an hour per participant. 3204 trials of data are collected from 17 participants.

### **4.6.1 Accuracy and reaction time**

The average time to finish the practice (three sets: set 1 - 3 in Figure 32) and the main session (five sets: set 4 - 8 in Figure 32) were 15.54 minutes and 20.9 minutes, respectively. The break time between trials in the practice and the main session was 4.19 seconds and 2.96 seconds, respectively. The break time between the practice and the main session was 7.67 minutes on average.

The learning effect across all eight sets (three sets in practice session plus five sets in main session equals 36.44 minutes) is statistically significant ( $p < .05$ ) in accuracy (Figure 32, top) and  $IT_{est}$  (Figure 32, bottom) but not in reaction time using a one-way ANOVA.

The highest set accuracy for the practice and the main session is 90.93 % (SD=9.69) and

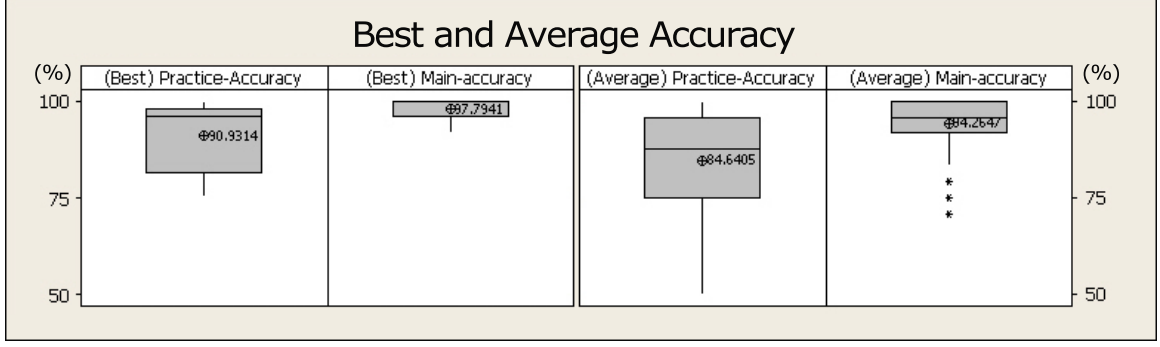


**Figure 32:** Learning effect in practice (set 1 - 3) and main session (set 4 - 8): Accuracy (top), Information transfer rate (bottom).

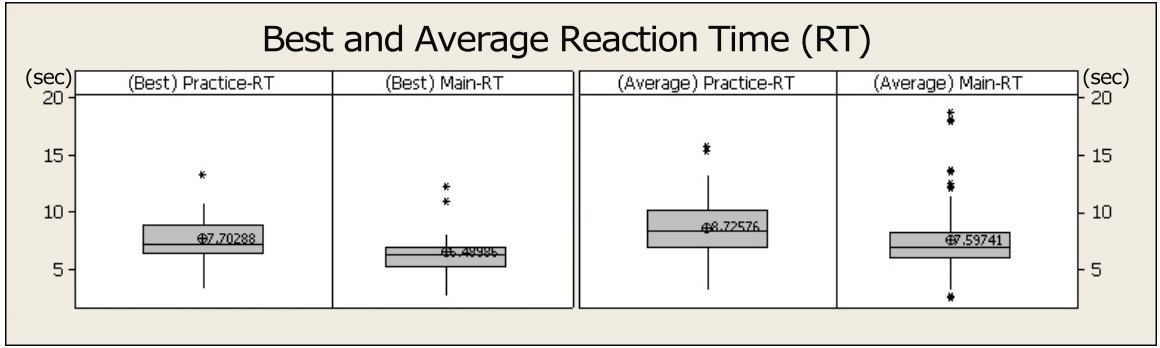
97.79 % (SD=2.99), respectively (Figure 33, left). Twelve out of 17 participants achieved 100% accuracy in at least one set. The average accuracy for the practice and the main session is 84.64% (SD=12.18) and 94.26% (SD=6.23), respectively (Figure 33, right).

The fastest set reaction time for the practice and the main session is 7.70 seconds (SD=2.28) and 6.49 seconds (SD=2.35), respectively (Figure 34, left). The average reaction time for the practice and the main session is 8.73 seconds (SD=2.67) and 7.60 seconds (SD=3.05), respectively (Figure 34, right).

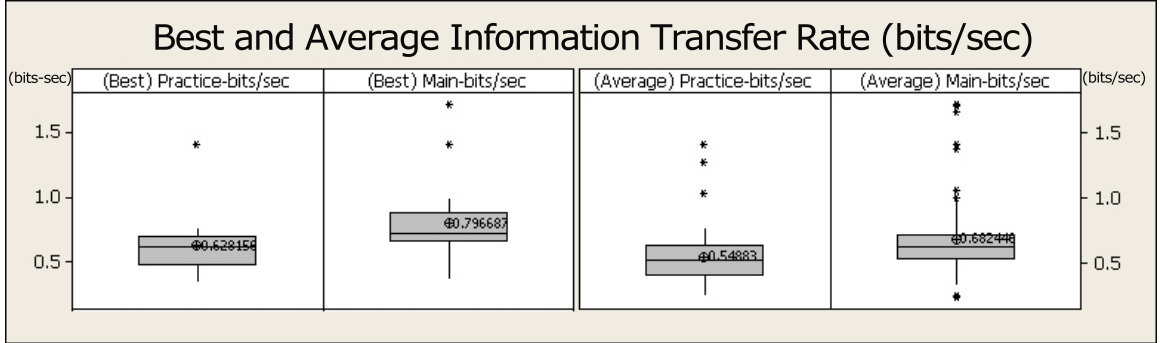
The highest information transfer rate (bits/second) for the practice and the main session



**Figure 33:** Accuracy: Best (left) and average (right).



**Figure 34:** Reaction time: Best (left) and average (right).



**Figure 35:** Information transfer rate: Best (left) and average (right).

is 0.63 bits/seconds (SD=0.23) and 0.80 bits/seconds (SD=0.33), respectively (Figure 35, left). The average information transfer rate for the practice and the main session is 0.54 bits/seconds (SD=0.22) and 0.68 bits/seconds (SD=0.30), respectively (Figure 35, right).

The average  $IT_{est}$  calculated by the formula 1 and  $2^{IT_{est}}$  (number of correctly recognized patterns) is 4.50 bits and 22 bits, respectively.

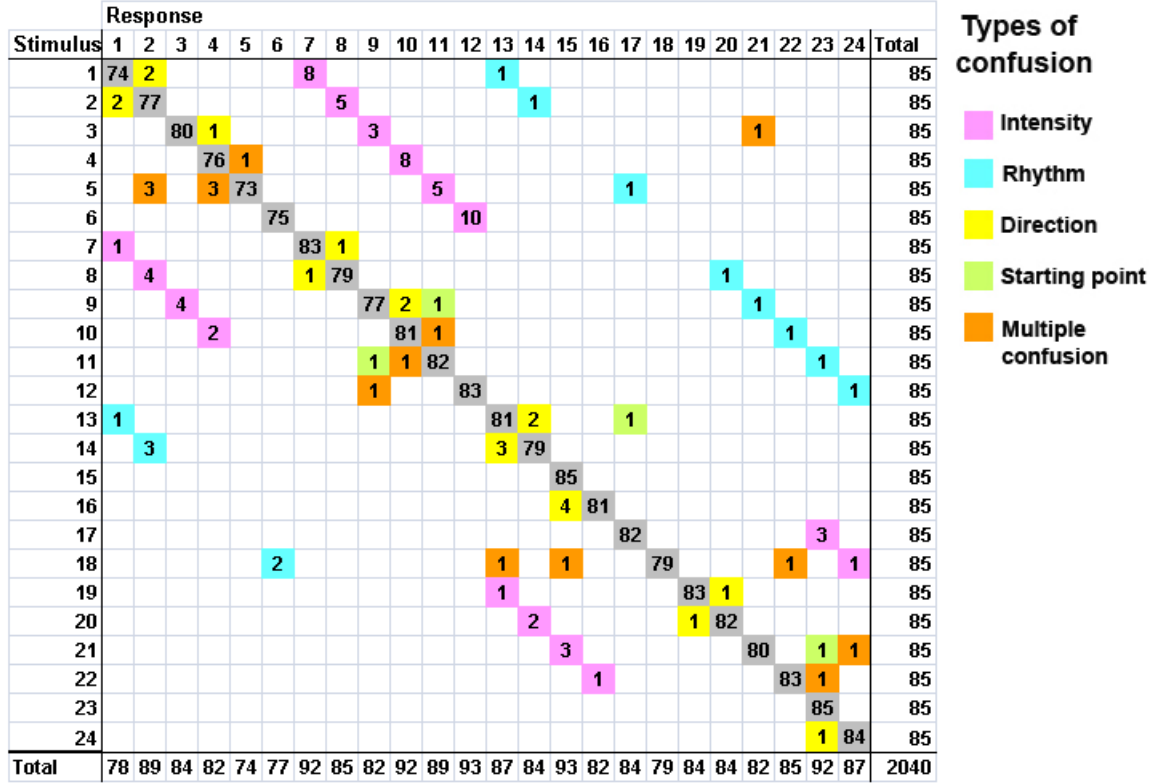


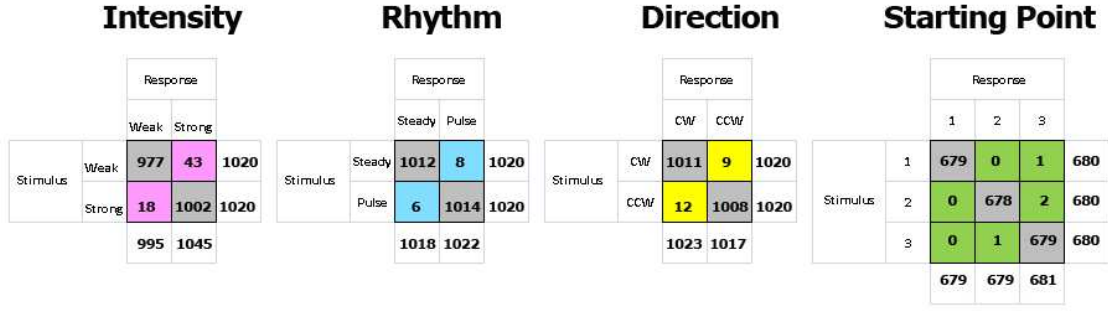
Figure 36: Confusion matrix in the main session.

#### 4.6.2 Confusion between parameters

The confusion matrix for the main session (set 4 - 8, 17 participants  $\times$  24 patterns  $\times$  5 repetition = 2040 trials, Figure 36) indicates that intensity is the hardest parameter to differentiate. 50.83% of the errors are caused by confusion between weak and strong patterns (Figure 38). However, this intensity confusion is reduced with practice (Figure 39). In the first set of the main session (set four), 64.5% of the errors were caused solely by the intensity confusion. This number decreases to 31.6% in set seven.

The average error caused by the intensity, direction, rhythm, and starting point parameters is 50.83%, 18.33%, 13.33%, and 3.33%, respectively. The confusion matrix for each parameter is illustrated in Figure 37.

A post-hoc analysis indicates that the effects of intensity (Figure 40, left,  $p < .01$ ) and rhythm (Figure 40, right,  $p < .01$ ) on accuracy are statistically significant using a one-way ANOVA. In general, patterns with strong intensity and pulsed rhythm are distinguished



**Figure 37:** Confusion matrix for each parameter (errors involving confusion with multiple parameters are not included).

**Table 10:** Relationship between parameter and performance in the main session (one-way ANOVA,  $p < .01$ ): ‘Y’ indicates that the relationship between column and row label is statistically significant, whereas ‘N’ indicates that the relationship between the column and row label is not statistically significant.

	Intensity	Rhythm	Direction	Starting point	Learning effect
Accuracy	Y	Y	N	N	N
Reaction Time	Y	N	N	N	Y

more correctly than patterns with weak intensity and pulsed rhythm. The average accuracy in patterns with strong and weak intensity is 96.18% (SD=6.66) and 92.35% (SD=6.79), respectively. The average accuracy in patterns with pulsed and steady rhythm is 96.47% (SD=4.87) and 92.06% (SD=8.02), respectively.

Similarly, the effects of intensity (Figure 41, left,  $p < .01$ ) and training (Figure 41, right,  $p < .01$ ) on reaction time are statistically significant using a one-way ANOVA. In general, reaction time becomes faster with more training and is faster on patterns with strong intensity. The average reaction time in patterns with strong and weak intensity is 6.88 seconds (SD=1.01) and 7.85 seconds (SD=1.18), respectively. The average reaction times in sets 4, 5, 6, 7, and 8 are 8.11 seconds (SD=1.03), 7.49 seconds (SD=1.40), 7.52 seconds (SD=0.96), 6.92 seconds (SD=1.20), and 6.78 seconds (SD=0.91), respectively.

The summary of the one-way ANOVA that explores the relationship between each parameter of the pattern design and learning effect in performance (i.e., accuracy and reaction time) is described in Table 10.

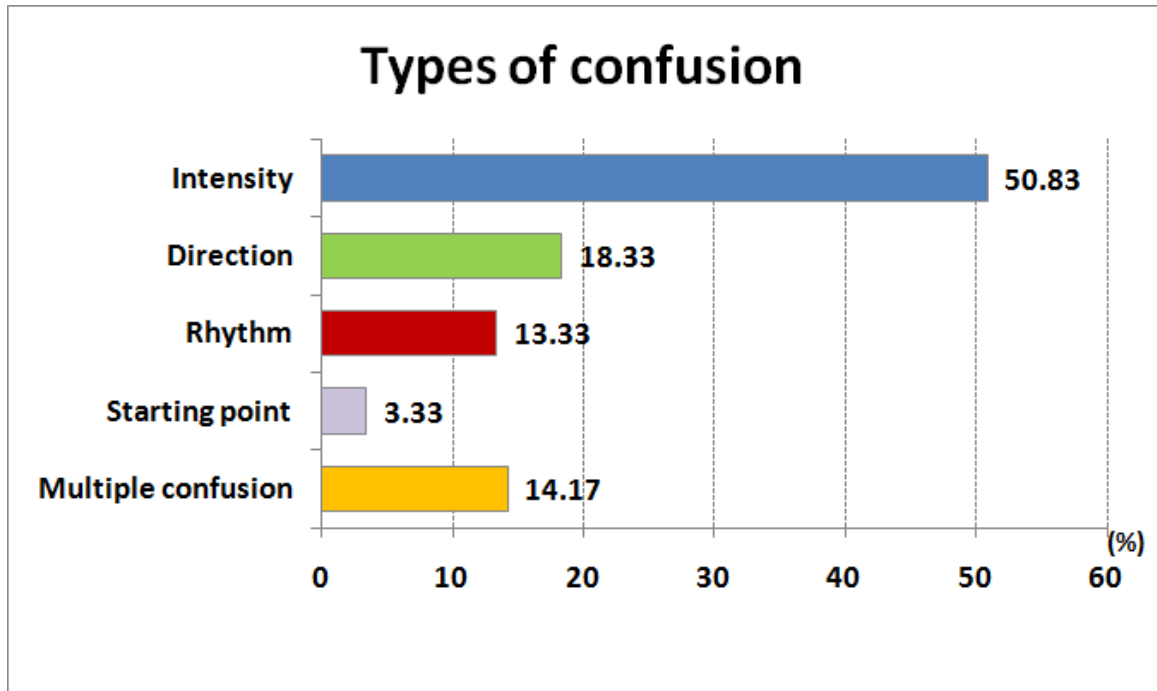


Figure 38: Types of confusion in the main session.

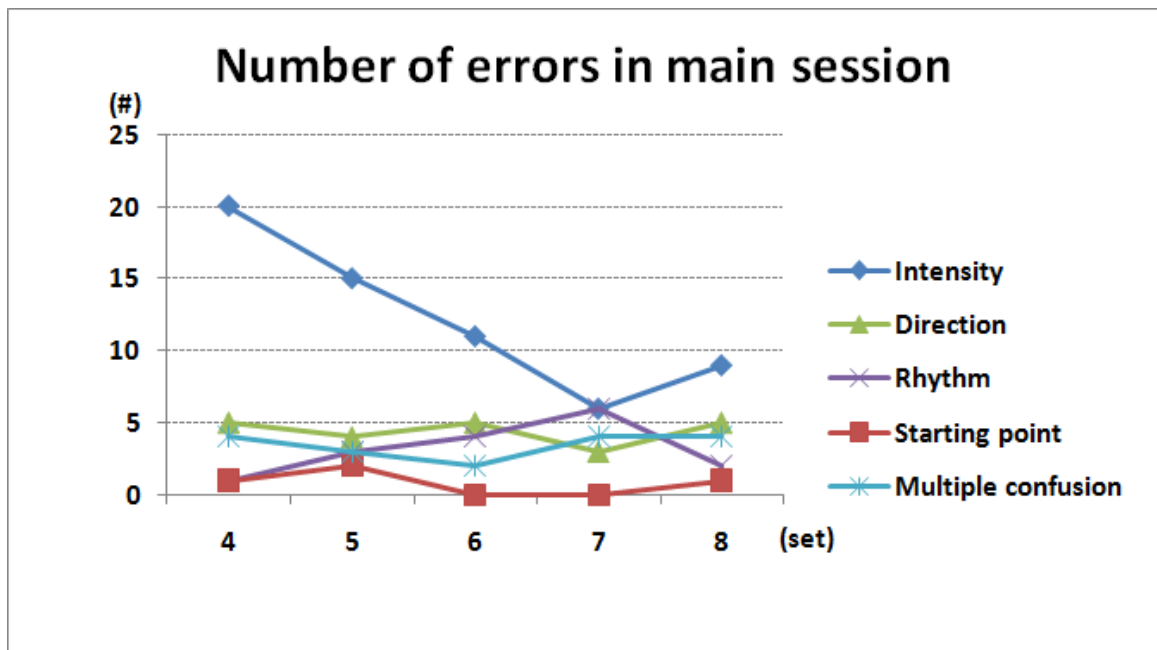
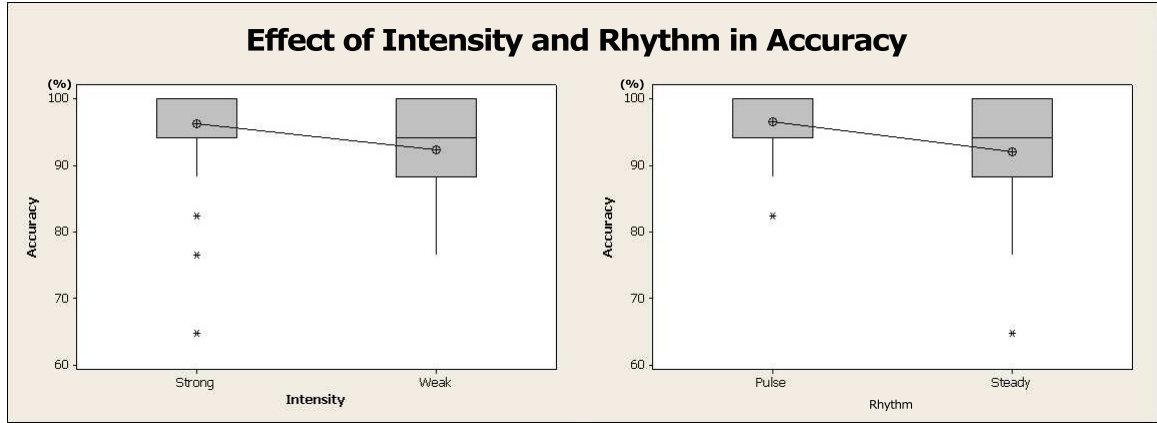


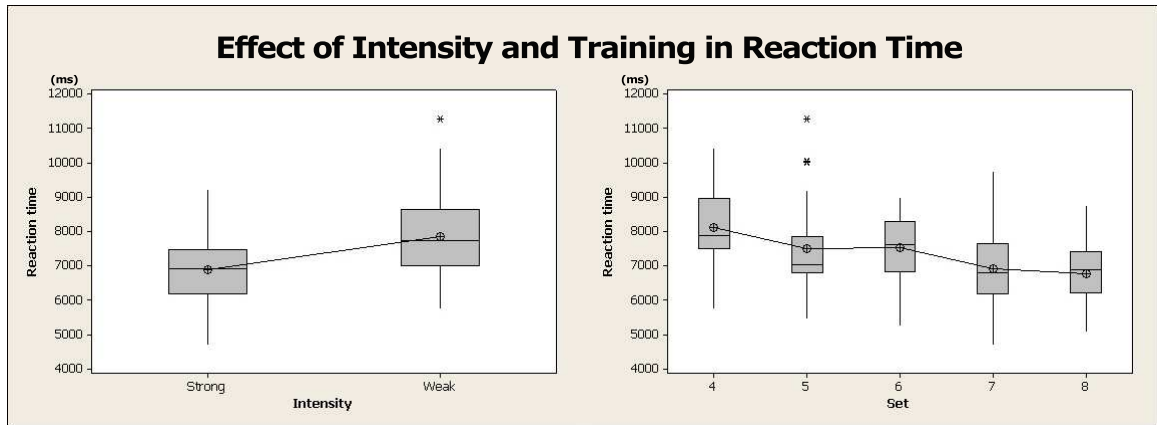
Figure 39: Number of errors in main session.

#### 4.6.3 User strategies and subjective ratings

The participants' subjective rating of the difficulty in perceiving each parameter (Figure 42) is slightly different from the confusion that was measured from the performance (Figure 38).



**Figure 40:** Effect of intensity (left) and rhythm (right) in accuracy in the main session (set 4 - set 8).

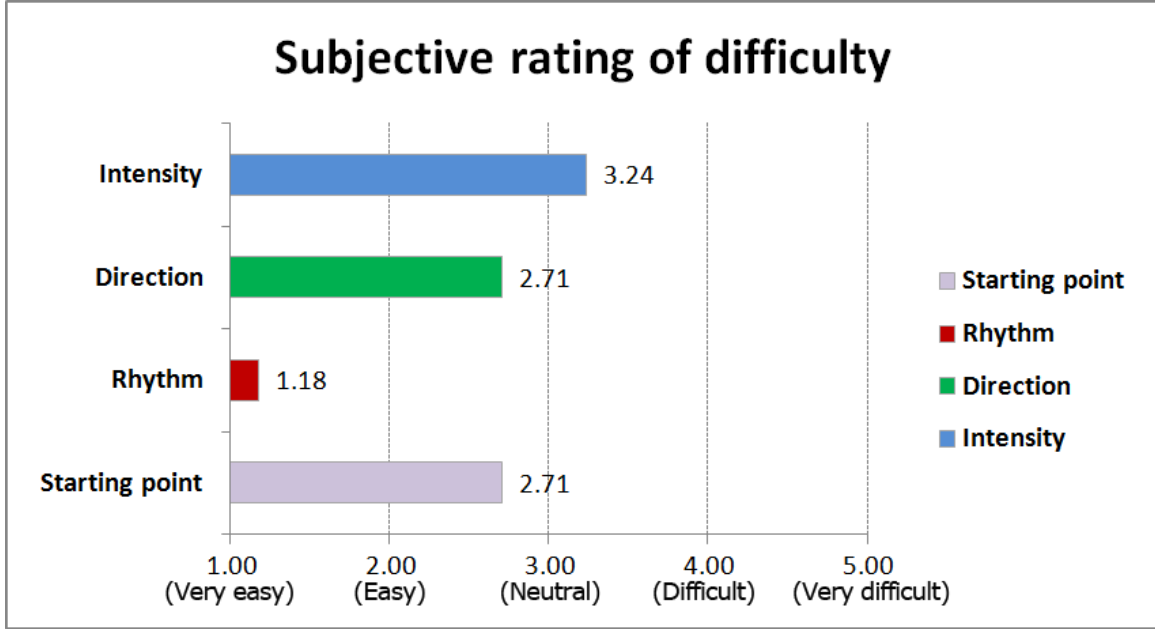


**Figure 41:** Effect of intensity (left) and training (right) in reaction time in the main session (set 4 - set 8).

Although more errors occurred confusing rhythm than starting point during the experiment, participants felt that perceiving rhythm was easier than perceiving the starting point. Using a Likert scale that ranged from 1 (very easy) to 5 (very difficult), participants reported that intensity was the most difficult parameter to perceive (3.24), followed by the starting point (2.71) and the direction (2.71). Rhythm was perceived as the easiest parameter to distinguish (1.18).

#### 4.6.3.1 Intensity

Difficulty in perceiving intensity was observed in two aspects. Some participants reported that the difficulty was caused by the fact that the difference between strong and weak



**Figure 42:** Subjective rating of the difficulty in perceiving each parameter.

patterns was not sufficient. On the other hand, other participants reported that although the difference between weak and strong patterns was sufficient, the weak pattern was too weak for them to clearly distinguish other parameters such as the starting point. Additionally, some participants reported that a weak pattern generated after a strong pattern was harder to discriminate. This result indicates that sensitivity to intensity in tactile patterns varies from person to person and from situation to situation. Interestingly, some participants reported that when the intensity changed in two consecutive trials, discriminating intensity of the latter trial was always easy. Whether the intensity was strong or weak, the contrast between the different intensity levels was perceived as an important cue in discriminating the intensity. This result indicates that the relative presentation of intensity enhances perception sensitivity, much as it does for frequency [9].

#### 4.6.3.2 Starting point

Difficulty in perceiving the starting point was observed in two aspects: hardware adjustment and adaptation effect. The tightness of the strap and location of the motor on the skin affected the participants' sensitivity in perceiving the starting point. Participants reported



that this difficulty was mostly eliminated by adjusting the hardware to the preferred position during the practice session. An adaptation effect was partially observed during the test. Some participants reported that they felt like the skin under a particular motor was immune to sensation.

#### *4.6.3.3 Direction*

Difficulty in perceiving direction was mostly caused by an unfamiliar mental model. Some participants reported that building a mental model for clockwise and counterclockwise was difficult. Other participants reported that matching the direction across different modalities (matching the tactile direction on the skin to the visual direction on the display) was difficult.

#### *4.6.3.4 Rhythm*

Difficulty in perceiving rhythm was rarely observed. Most people reported that they could easily discriminate the rhythm. The easy perception of the rhythm affected people's strategy for narrowing the selection from 24 patterns. When building a strategy to narrow the selections, subjects began by discriminating the rhythm. The rest of the procedure varied from person to person.

### **4.6.4 Summary**

After 40 minutes of training, participants achieved 98% accuracy and a reaction time of 6.5 seconds when discriminating 24 tactile patterns. The average information transfer (bits), the bits per second, and number of correctly recognized patterns were 4.50 bits, 0.74 bits/second, and 22 patterns, respectively.

Among four parameters that were investigated in this experiment (intensity, starting point, rhythm, and direction), intensity was the most difficult parameter to perceive. One-way ANOVAs indicate that accuracy is affected by intensity and rhythm, and reaction time is affected by intensity and training. Stronger intensity facilitates higher accuracy and faster reaction time, and pulsed rhythm enhances accuracy. The subjective ratings and self reports indicated that people had difficulty discriminating intensity, direction, and starting

point for various reasons. However, difficulty caused by the rhythm was rarely observed.

This experiment was performed at two sites: Georgia Institute of Technology and ETRI. The difference in accuracy and reaction time between sites was not statistically significant.

#### ***4.7 Discussion: Tactile information transfer for microinteractions***

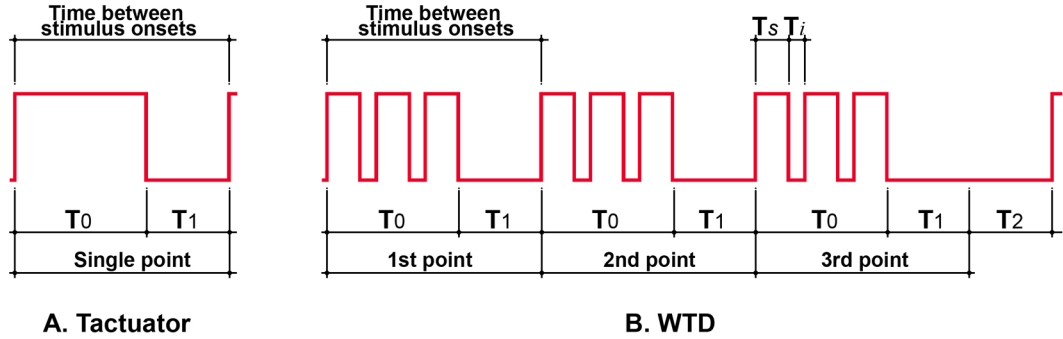
Microinteractions refer to interactions with a device that take less than four seconds from initiation to completion [1]. In a mobile computing environment, the average duration that on-the-go users concentrate on incoming information while walking in a crowded environment was observed as four seconds [90]. Thus, a temporal restriction should be considered when designing interfaces for on-the-go users. In this case, all alerts were less than 2.5 seconds, meeting the four second requirement. However, the current patterns still need to be improved to enable more microinteraction-friendly interactions.

The Tactuator [114] and the WTDs tested in this chapter apply a similar approach for designing tactile patterns and evaluating tactile perception (through the calculation of  $IT_{est}$  - Table 11). Although the difference between the two systems in  $IT_{est}$  is minimal, the difference in  $IT_{est}$  rate (bits/sec) is significant due to several differences: the level of proficiency (expert vs. novice); number of steps (1 vs. 3); stimulus onsets (125, 250, 500 ms in stimulus and 20 – 500 ms in interval vs. 400 ms in stimulus and 250ms in interval); and  $IT_{est}$  rate calculation criteria ( $IT_{est}$ /stimulus onsets vs.  $IT_{est}$ /reaction time). Because of these differences, direct comparison between the Tactuator and my WTD may be implausible. However, the contrast between the  $IT_{est}$  rates may be used to improve the design of current tactile patterns.

The fact that the tactile pattern is composed of a series of localized stimulations or stimuli is both an advantage and a disadvantage for directional patterns. As reported by the participants of the Chapter 5 experiments, who were asked to detect directional tactile patterns on the wrist while in a distracted condition, users could easily catch the pattern of the alerts even when they failed to perceive the first location out of the three points. The constant movement of the tactile stimulation provided useful directional cues when estimating the spatial configuration of the pattern. However, in the tactile patterns that

**Table 11:** Comparison between Tactuator and WTDs:  $T_0$  = Stimulus length on a single point,  $T_1$  = ISI (Tactuator) or interval between points (WTD),  $T_2$  = repetition interval applied to the 3rd point,  $T_s$  = single pulse stimulus,  $T_i$  = stimulus between pulses

	<b>Tactuator</b> [114]	<b>Tactile patterns in current chapter</b>
$IT_{est}$	5.6 – 6.5 bits	4.5 bits
$IT_{est}$ rate (bits/sec)	12 bits/sec	0.74 bits/sec
<b>Level of proficiency</b>	Expert	Novice
<b>Number of steps in a pattern</b>	1	3
<b>Pattern duration calculation</b>	$T_0 + T_1$	$(T_0 + T_1) \times 3 + T_2$
<b>Stimulus onsets</b>	$T_0$ : 125, 250, 500 ms $T_1$ : 20 – 500 ms (Figure 43, left)	$T_0$ : 400 ms, $T_1$ : 250 ms $T_2$ : 300 ms $T_s$ : 100 ms, $T_i$ : 50 ms (Figure 43, right)
$IT_{est}$ rate calculation	$IT_{est}$ /stimulus onsets	$IT_{est}$ /reaction time
<b>Tactile parameters</b>	Waveform (frequency + intensity), site, stimulus length	Intensity, direction starting point, rhythm



**Figure 43:** Temporal pattern schematic (Tactuator [114] and WTD):  $T_0$  = Stimulus length on a single point,  $T_1$  = interval,  $T_2$  = segmentation interval between repetition,  $T_s$  = stimulus length within a pulse,  $T_i$  = interval between pulses.

have directional components, the time between stimulus onsets is multiplied by the number of involved actuators and increases the total duration. If the pattern is repeated, it is another temporal disadvantage that increases the pattern duration (Figure 43-B). These factors lengthen the reaction time and eventually lower the  $IT_{est}$  rate when the  $IT_{est}$  rate (bits/second) is calculated with the  $IT_{est}$  rate divided by the reaction time. Thus, to improve the  $IT_{est}$  rate, the temporal pattern should be carefully designed to minimize the

directional cues and stimulus onsets.

In addition to the temporal configuration, the design of the tactile texture is another possible direction to enhance the  $IT_{est}$  rate. For example, although my experiments show that intensity is a problematic feature that causes confusion, increases subjective difficulty, and delays reaction time, a redundant coding that combines intensity and frequency may enrich the texture profile of the waveform and eventually improve the patterns' discernability.

#### **4.8 *Summary of the chapter***

As I hypothesized in Table 8, the result of the experiment in this chapter illustrated that tactile displays on the wrist are appropriate to deliver directional patterns. After less than one hour of training, participants achieved accuracies up to 98% and reaction times of about 6.5 seconds on average when discriminating 24 tactile patterns. Among the four parameters that were used to design the tactile patterns in this chapter, rhythm and intensity were the easiest and the most difficult parameters to distinguish, respectively.

Although the experiment in this chapter proved that WTDs can enable tactile alerts on the wrist, it is unclear whether tactile patterns on the wrist are distinguishable while the user is distracted. Since the mobile computing environment is associated with various distraction, the benefit of WTDs in distracted conditions will be explored in the next chapter.

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## CHAPTER V

### TACTILE ALERT PERCEPTION WITH VISUAL DISTRACTION

In mobile computing, alerts for incoming phone calls are often triggered in an unpredictable moment when users are not fully ready for the interaction. That is, while the user interacts with the world (e.g., driving or walking), events generated from mobile devices can be easily missed or ignored. Sometimes, the incoming alerts from mobile devices are missed because of a lack of attentional resources or proximity. Other times, those alerts are ignored because of a lack of dexterity or social willingness. Types of distraction that hinder interaction with mobile devices while on-the-go depend on the types of interaction with the world in which users are more or less engaged. For example, when the user is driving or walking in the street, the ability to reach the phone in a bag and check an incoming phone alert may be dependent upon the user's engagement in preoccupying tasks.

In this chapter, I investigate the effect of WTDs on reducing visual distraction. The first half of the chapter discusses experiments that were performed at the Georgia Institute of Technology <sup>1</sup>. The second half of the chapter explores possible confounds that were discovered from the experiment.

Assuming that the failure to facilitate ready-at-hand interaction with mobile devices is caused by a lack of visual attention and proximity, the wrist-worn WTDs are expected to enable non-visual and immediate perception of incoming alerts. Table 12 shows the overview and goal of the study in this chapter.

In this chapter exploring the effect of WTDs in visually distracted conditions, I define two main concepts (primary and secondary task) associated with the design of the experiments as follows:

- Primary task: A task that engages people with the world (e.g., walking, monitoring

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<sup>1</sup>Parts of this chapter have been published in the SIGCHI Conference on Human Factors in Computing Systems (CHI) [67].

**Table 12:** Overview of the study outlined in Chapter 5

Research Question	Hypothesis	Method	Data Collected	Analysis
Research Question 2 subpart: A. How much is the secondary task (alert perception) affected by the primary task (visual search task)? B. How much is the primary task (visual search task) affected by the secondary task (alert perception)?	I hypothesize that the alert perception through WTDs is 1) less distracted by the primary task and 2) less distracting to the primary tasks than existing mobile phone alerts.	Adults participate in controlled settings (within-subject) and perform in five single task and six dual task conditions. Single task is composed of the primary task with three difficulty levels (easy, moderate, difficult) and secondary task with two devices (perceiving alert from a WTD and a mobile phone). Dual task is composed of the combination of one primary task and one secondary task.	1. Speed and accuracy of alert perception in single and dual task conditions (quantitative). 2. Speed and accuracy of visual search task in single and dual task condition (quantitative). 3. Performance difference of the primary task caused by the secondary task, and vice versa (quantitative). 5. NASA-TLX workload assessment (quantitative). 6. Semi-structured interview (qualitative).	1. Calculate the performance difference of the accuracy and reaction time for the secondary tasks in single and dual task condition to learn the effect of the primary task, and vice versa. 2. Assessing user-constructed strategy, if any, through interview. 3. Assessing the workload of each condition through NASA-TLX and interview.

the environment, talking, etc.)

- Secondary task: A task that engages people with mobile devices (e.g., answering a phone call)

A visual search task is selected as the primary task to be performed in the experiment in this chapter. The user must report the presence or absence of a target number among a field of numbers. Visual search tasks are commonly used in psychophysics and HCI research [128, 130] to assess attention and performance difficulty. In this chapter, the visual search task simulates the situation in which visual attention is required for interacting with the world. Perceiving incoming alerts from two mobile systems, a WTD on the wrist and a mobile phone in the pocket, will be the secondary task in the experiment. The phone alert perception task provides a baseline similar to that which frequently happens with existing mobile devices. To explore how the primary and secondary task distract each other, the performance of these three tasks (the visual search task, the alert perception task with the WTD, and the alert perception task with the phone) are tested with and without distraction.

### 5.1 Research questions and hypothesis

This study is designed to explore Research Question 2 and its subquestions:

**Research Question 2 :** Can tactile alerts on WTDs be perceived while the user is visually distracted?

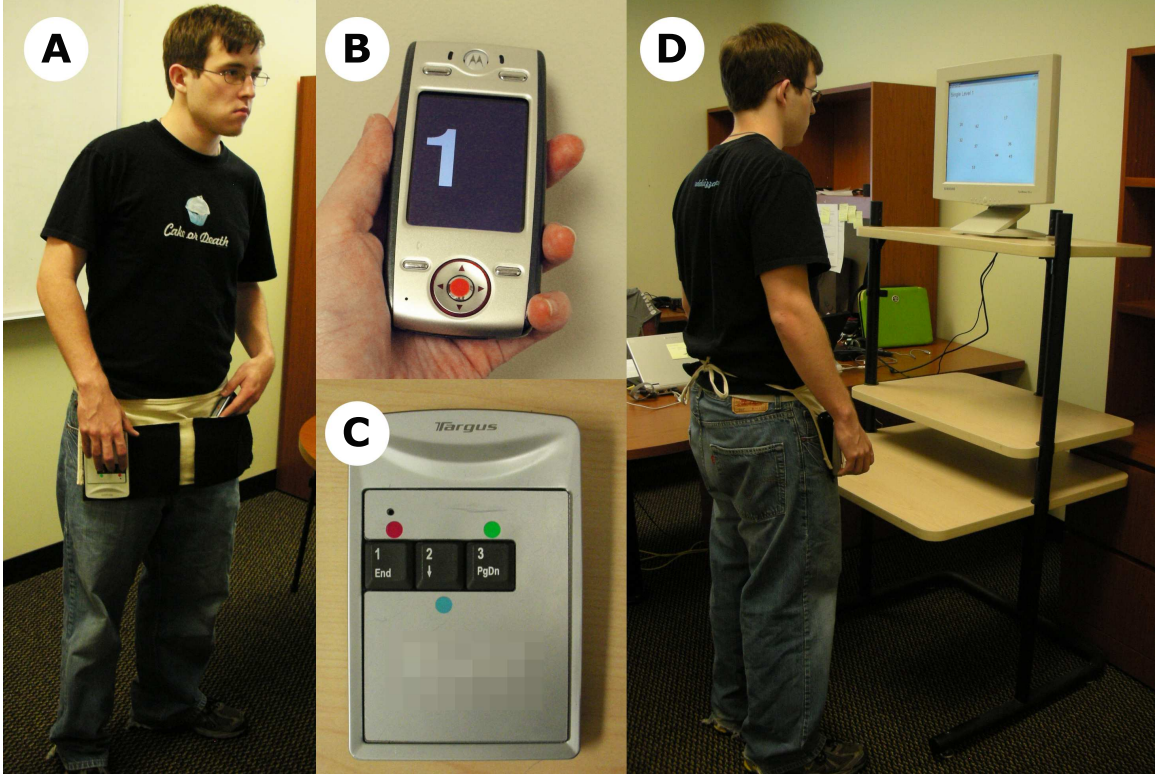
1. How much is the secondary task (alert perception with a WTD or a mobile phone) affected by the primary task (visual search task)? (Figure 2, arrow 1 & 2)
2. How much is the primary task (visual search task) affected by the secondary task (alert perception with the WTD and the mobile phone)? (Figure 2, arrow 3 & 4)

Based on the assumption that alerts generated from WTDs are more immediate and intimate than alerts from mobile phones, I generated hypotheses for these two subquestions as listed below:

**Hypothesis :** I hypothesize that the alert perception through WTDs is 1) less distracted by the primary task and 2) less distracting to the primary tasks than existing mobile phone alerts.

1. When people are visually distracted, perceiving tactile alerts through the WTD on the wrist is easier than alert perception from the phone.
2. When comparing alert perception in the single task condition to the dual task condition where the user is visually distracted, the performance difference in alert perception caused by the visual distraction is less with the WTD than the mobile phone.
3. When people perform visual search tasks, alerts from the WTD on the wrist distract from the search task less than alerts from the mobile phone.
4. When comparing the visual search task in the single task condition and the dual task condition where the user is distracted by incoming alerts from the WTD and phone, the performance difference caused by the WTD is less than the difference caused by the mobile phone.

Based on these hypotheses, my analysis will focus on the performance difference between single and dual task conditions for the three tasks explained above: visual search task (primary), alert perception from a WTD (secondary) and alert perception from a mobile phone (secondary).



**Figure 44:** Test setting: A) Front view of the participant wearing an apron with pockets. A wireless keypad is attached on the dominant hand side of the apron and a mobile phone is placed in the pocket of the non-dominant hand side. B) A visual alert from the mobile phone. C) A wireless keypad with three buttons for entering the perceived pattern. D) A monitor is set at the eye level of the participant to display primary tasks.

## 5.2 Study setting

The experiment is performed in a quiet lab setting at the Georgia Institute of Technology. Participants stand and watch a monitor that is set at eye level while wearing a WTD and an apron (Figure 44). The WTD is worn on the non-dominant hand. A wireless keypad is attached at the dominant hand side of the apron to ensure eyes-free interaction when the participant presses a key to respond to the secondary task. A mobile phone is stored in the non-dominant hand side of the pocket of the apron. To avoid possible audio cues generated from the motors, participants wear ear plugs and headphones. The three main dependent variables for quantitative analysis are accuracy, reaction time and information transfer ( $IT_{est}$ ).



### ***5.3 Software and equipment***

Tactile alerts on the WTD are controlled by a Wiring <sup>TM</sup> microcontroller which is connected to a laptop computer. Software written in Java communicates with the Wiring <sup>TM</sup> microcontroller and collects log data with time stamps. For the phone alert perception task, the software is implemented in Python on a Motorola E680i touch screen camera phone. The visual search task is presented on a monitor at the subject's eye level using software written in Java. The performance of the visual search task is audio- and video-recorded for future analysis.

### ***5.4 Task and apparatus***

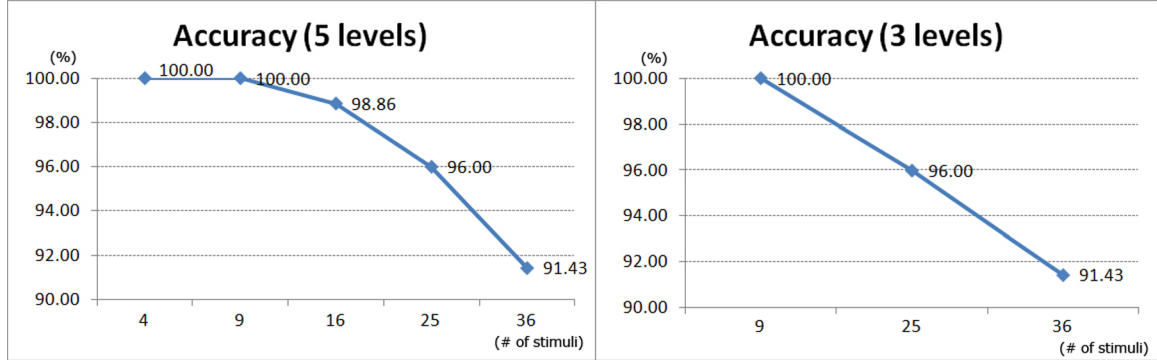
Experiments in this chapter are designed to explore subjects' alert perception for the secondary task while distracted by the primary task and vice versa. Here and throughout the paper, I define single task condition, dual task condition, distraction, and difficulty as follows:

- Single task condition: A test condition in which the participant performs only one task at a time.
- Dual task condition: A test condition in which the participant performs two tasks (one primary task and one secondary task) at the same time.
- Distraction: Independent variable. Indicates whether the task is simultaneously performed with the other task or not. In the dual task condition, the secondary task causes a distraction to the primary task, and vice versa.
- Difficulty: Independent variable. Three levels of difficulty are provided in the primary task (level 1 = easy, level 2 = moderate, level 3 = difficult).

A visual search task with three difficulty levels (easy, moderate, difficult) is provided in both the single and dual task conditions (Figure 46). Dual tasks are composed of one primary task and one secondary task. The mode of the stimulus-response (S-R) interaction

**Table 13:** Modality of stimulus and response in each task

	Task	Stimulus	Response
Primary	Visual search task	Visual	Vocal
Secondary	WTDs	Tactile	Motor
	Mobile phone	Tactile + visual	Motor

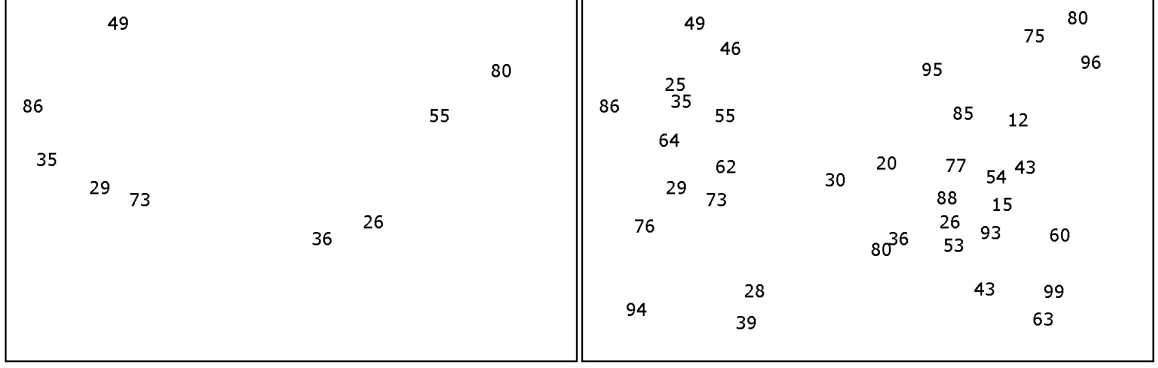
**Figure 45:** Pilot test result for the primary task: Five levels for the test (left), Three selected levels (right).

of the primary and secondary tasks are designed to avoid a modality conflict in the dual task condition (Table 13).

#### 5.4.1 Primary task

A forced-choice visual search task with three difficulty levels is provided as the primary task. Participants are asked to search for the target stimulus (i.e., the number 57) among other two-digit numbers on a screen within five seconds and verbally respond with ‘yes’ or ‘no.’ Every five seconds a beep sounds as an audio cue to indicate when a new trial begins. 50% of the trials contain the target stimulus, and trials are presented in random order. The location and combination of two-digit numbers presented in each trial is randomly selected. Participants stand while facing a screen that is raised to eye level (Figure 44D). The modality for the S-R channel (i.e., screening visually and responding verbally) is selected to avoid modality conflict with the secondary tasks (Table 13). The difficulty level is controlled by the number of stimuli (i.e., two-digit numbers) presented in each trial. Nine, 25, and 36 stimuli are displayed in levels 1, 2, and 3, respectively (Figure 46).

The number of stimuli selected to provide the three difficulty levels for the primary task



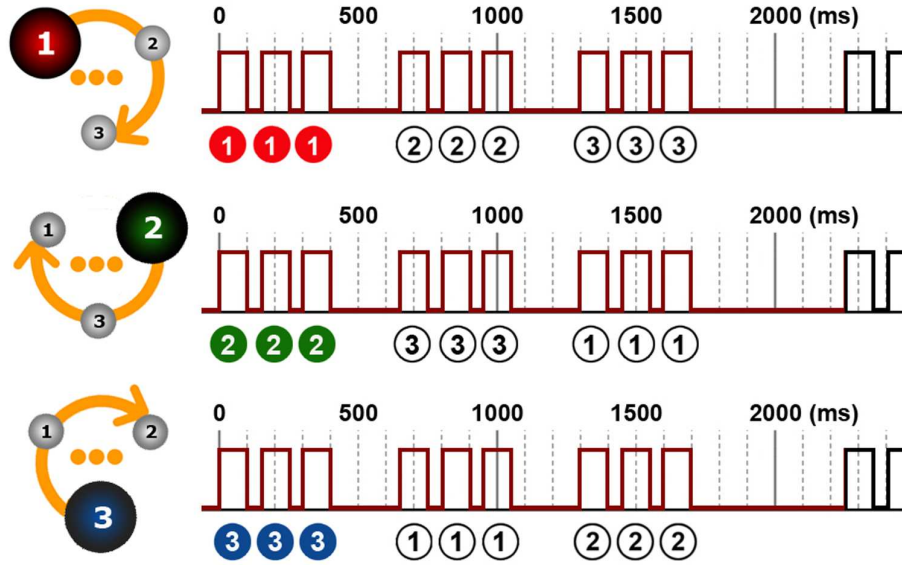
**Figure 46:** Primary task example: Level 1 with nine two-digit numbers (left), Level 3 with 36 two-digit numbers (right).

was determined by a pilot test. In a pilot test with seven participants, visual screening performance with five levels (i.e., 4, 9, 16, 25, and 36 stimuli) was measured (Figure 45, left). Participants were asked to find ‘57’ in the screen and provide a vocal response. For each participant, 30 trials with five-second intervals were provided for each level (30 trials  $\times$  5 levels  $\times$  7 participants = 1050 trials). Based on the results of the pilot test, three levels with 9, 25, and 36 stimuli were selected (Figure 45, right) because the resulting accuracies (and presumably the difficulties) were evenly distributed as 99%, 95%, and 91%. A five second interval was long enough to perform the task with nine stimuli. However, subjects rarely provided the answer within five seconds when finding the target number among 36 stimuli.

#### 5.4.2 Secondary task

The secondary tasks explore the subjects’ ability to perceive three types of alerts from the WTD worn on the wrist or the mobile phone (Motorola E680i camera phone with touch screen display) stored in the pocket.

In a preliminary survey, 69% of participants (nine males and one female) reported that their preferred place to store their phone is in a pocket (echoing the survey conducted by Cui et al. [26]). Thus, I used an apron with pockets to standardize the process of device acquisition and alert perception with the mobile phone (Table 17). A wireless keypad is attached on the surface of the dominant hand side of the pocket to enable vision-free motor



**Figure 47:** Patterns with three starting points: 1 (top), 2 (middle), and 3 (bottom).

responses. A mobile phone is stored on the non-dominant hand side of the pocket (Figure 44A). All keys in the wireless keypad except three buttons are deactivated and covered with a plastic lid to avoid motor errors (Figure 44C). Participants are asked to stand during the test to ensure easy access to the mobile phone in the pocket.

For the trial with the mobile phone, a four-second vibrating alert (two times  $\times$  2 seconds) is generated along with a visual alert that displays 1, 2, or 3 on the phone (Figure 44B). Once the participant perceives the vibration alert from the phone, she takes the phone out of the pocket, reads the number on the screen, presses the corresponding button on the wireless keypad, and restores the phone to the pocket. The S-R modality (Table 13) for the phone alert task is designed to simulate representative interactions in the real world.

In the test with the WTD, participants are asked to wear the tactile display on their non-dominant wrist. Three tactile patterns were selected based on the result of the first experiment (Figure 47). In these three patterns, the starting point varies (1, 2, and 3), but direction (clockwise), intensity (strong), and rhythm (pulsed) are constant. Once the participant perceives the pattern of the incoming alert on the wrist, she keys the appropriate response on the wireless keypad.

**Table 14:** Conditions and tasks of the experiment conducted in this chapter (numbers in parenthesis indicate the number of trials for each task in each condition): L1=level 1 (easy), L2=level 2 (moderate), L3=level 3 (difficult), W=WTD, P=phone

	Single task					Dual task					
ID	S1	S2	S3	S4	S5	D1	D2	D3	D4	D5	D6
Primary	L1 (60)	L2 (60)	L3 (60)	- -	- -	L1 (60)	L2 (60)	L3 (60)	L1 (60)	L2 (60)	L3 (60)
Secondary	- -	- -	- -	W (3×5)	P (3×5)	W (3×5)	W (3×5)	W (3×5)	P (3×5)	P (3×5)	P (3×5)

### 5.5 Procedure

With the primary task with three difficulty levels and two secondary tasks, the study design consists of eleven conditions: five single task conditions and six dual task conditions (Table 14).

The number of conditions (N) is calculated from Formula 2. In this formula, P and S refer to the number of primary and secondary tasks, respectively. In Table 14, the total number of conditions ( $3 + 2 + 3 \times 2 = 11$ ) is calculated from the primary task with three levels (L1, L2, L3) and the secondary task with two devices (W, P).

$$N = (P + S) + (P \cdot S) \quad (2)$$

Since individual sensitivity varies in perceiving tactile stimuli, a within-subject design is used in this experiment. The order of the task conditions (visual search task, alert perception task from the WTD and alert perception task from the mobile phone) and distraction conditions (single and dual task) are balanced ( $3 \times 2 \times 2 = 12$  orders). The order for the three difficulty conditions (levels 1, 2, and 3) in the primary task is randomized.

The experimental procedure is divided into three sessions: practice, main, and post. In the practice session, five trials for each level in the primary task ( $3 \text{ levels} \times 5 \text{ trials} = 15 \text{ trials}$ ) and six trials for each device in the secondary task ( $2 \text{ devices} \times 3 \text{ patterns} \times 2 \text{ trials} = 12 \text{ trials}$ ) are provided as single tasks. Since the spatial configuration between the three motors in the WTD (triangular) and three buttons in the keypad (linear) is inconsistent,

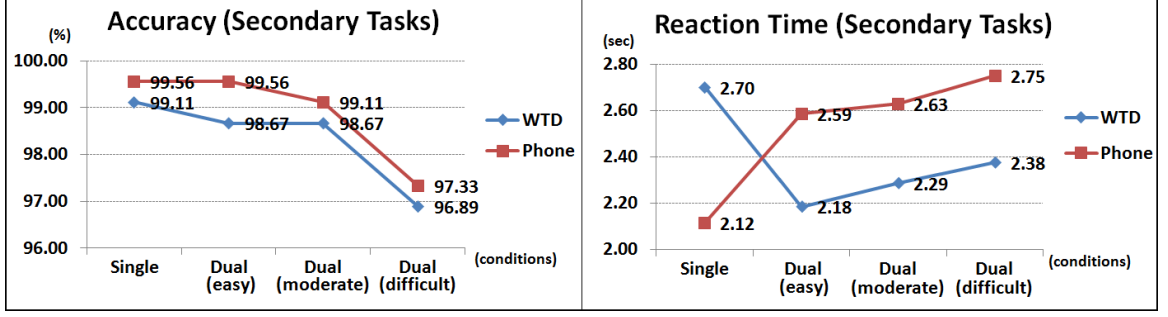
participants are asked to build their own mental mapping between the two during the practice session. Lessons learned from this procedure will be discussed in Chapter 6.

In the main session, data for accuracy and reaction time is logged from the secondary task, and audio and video is recorded of the primary task. Primary tasks with three levels and secondary tasks with two devices are tested both in the single and dual task conditions (Table 14). In the single task conditions (Table 14, S1-S5), the results of the three primary tasks and two secondary tasks are measured separately. In the dual task conditions (Table 14, D1-D6), each level of the primary task is paired with each device of the secondary task. When performing dual tasks, participants are asked to prioritize any task according to their own preference. This strategy, the loading-task technique of the performance-resources function (PRF, Figure 10-right, [129]) is selected because the research question of the experiment is related to the performance loss of both the primary and secondary tasks. The number of trials in each condition for the primary and secondary tasks is 60 and 15, respectively. The interval between trials in the primary task is five seconds ( $5 \text{ seconds} \times 60 \text{ trials} = 5 \text{ minutes/condition}$ ). The interval between trials in the secondary task is randomly set to between six and 18 seconds (12 seconds average). The duration for the secondary task depends on the subject's reaction time. Participants have a short break every 15 minutes to avoid fatigue.

In the post session, a semi-structured interview and a workload assessment survey is performed with the modified NASA-TLX focusing on the mental, physical, and temporal demand.

## **5.6 Results**

Sixteen subjects recruited at the Georgia Institute of Technology participated in this experiment (six female, ten male, mean age 26.69). The test duration was approximately one hour and thirty minutes. The order of each task (visual search task, alert perception from the WTD, and alert perception from the mobile phone) and distraction condition (single and dual task) were balanced ( $3 \times 2 \times 2 = 12$  orders). The order for three difficulty levels (levels 1, 2, and 3) in the primary task was randomized. The order for the 13th, 14th, 15th,



**Figure 48:** Secondary task: Accuracy (left), Reaction time (right).

and 16th participant was identical to the 1st, 4th, 7th, and 10th participant. The data from one participant who did not follow the described procedure was excluded from the analysis.

From the single task conditions, 2700 trials of data ( $3 \text{ levels} \times 60 \text{ trials} \times 15 \text{ participants}$ ) and 450 trials of data ( $2 \text{ devices} \times 15 \text{ trials} \times 15 \text{ participants}$ ) were collected from the primary and secondary tasks, respectively. From the dual task conditions, 5400 trials of data ( $3 \text{ levels} \times 2 \text{ devices} \times 60 \text{ trials} \times 15 \text{ participants}$ ) and 1350 trials of the data ( $2 \text{ devices} \times 3 \text{ levels} \times 15 \text{ trials} \times 15 \text{ participants}$ ) were collected from the primary and the secondary tasks, respectively. Independent variables for the primary task are difficulty (levels 1, 2, and 3) and distraction (no distraction, distraction from a WTD, and distraction from a phone). Independent variables for the secondary task are alert type (WTD and phone) and distraction (single and dual task).

### 5.6.1 Secondary task: accuracy, reaction time, and information transfer rate

The accuracy in perceiving incoming alerts with the WTD and the mobile phone is above 96% in all conditions (Figure 48). In the perception task with the WTD, the difference between single (S4 in Table 14), dual-easy (D1 in Table 14), dual-moderate (D2 in Table 14), and dual-difficult (D3 in Table 14) condition is not statistically significant in both reaction time and accuracy as determined by one-way ANOVA ( $p > .05$ ). The result of paired t-test that compares one condition to the other (Table 15) indicates that the difference between two conditions in each pair is statistically significant only in two pairs—single and dual-easy pair (S1 and D1,  $p=0.018$ ) and dual-easy and dual-difficult pair (S1 and D3,  $p=0.041$ )—with respect to the reaction time. No statistically significant result between the paired

**Table 15:** P value of the paired t-test with respect to the reaction time (upper triangle) and accuracy (bottom triangle) of alert perception through a WTD. Numbers in parentheses indicates the condition ID that is defined in Table 14.

	Single (S4)	Dual-easy (D1)	Dual-moderate (D2)	Dual-difficult (D3)
Single (S4)	-	0.018	0.145	0.178
Dual-easy (D1)	0.656	-	0.262	0.041
Dual-moderate (D2)	0.656	1.000	-	0.383
Dual-difficult (D3)	0.096	0.207	0.207	-

**Table 16:** P value of the paired t-test with respect to the reaction time (upper triangle) and accuracy (bottom triangle) of alert perception through a phone. Numbers in parentheses indicates the condition ID that is defined in Table 14.

	Single (S5)	Dual-easy (D4)	Dual-moderate (D5)	Dual-difficult (D6)
Single (S5)	-	0.000	0.000	0.000
Dual-easy (D4)	1.000	-	0.576	0.140
Dual-moderate (D5)	1.000	1.000	-	0.371
Dual-difficult (D6)	0.004	0.007	0.007	-

conditions is observed with respect to the accuracy.

Interestingly, when comparing the WTD in the single task condition (S4 in Table 14) versus the dual task with level 1 difficulty (D1 in Table 14), the reaction time to perceive incoming tactile alerts is faster in the visually distracted condition (D1). As the amount of distraction increases to the moderate (level 2: D2 in Table 14) and difficult levels (level 3: D3 in Table 14), the reaction time decreases when perceiving incoming tactile alerts. However, reaction time to perceive incoming tactile alerts in the most difficult dual task condition (D3) is still faster than the single task condition (S4). I will discuss this counter-intuitive benefit of distraction later in this chapter.

In the perception task with the phone, the difference between single (S5 in Table 14), dual-easy (D4 in Table 14), dual-moderate (D5 in Table 14), and dual-difficult (D6 in Table 14) condition is statistically significant in both reaction time and accuracy as determined by one-way ANOVA ( $p < .05$ ). This result indicates that the visual distraction consistently affects the alert perception through the phone. The result of the paired t-test that compares one condition to the other (Table 16) indicates that the difference between single task condition (S5) and each dual task condition—dual-easy (D4,  $p = 0.000$ ), dual-moderate



**Table 17:** Time stamp events in stimulus-response cycle for phone alert task

Interaction	Time stamp events
Event1. Alert is generated	Constant darkness Alert is generated
Event2. Participant pulls the phone from the pocket	Light level changes to bright.
Event3. Participant clicks the button on the keypad	Constant brightness. Button press
Event4. Participant replace the phone to the pocket	Light level returns to dark.

(D5,  $p=0.000$ ), and dual-difficult (D6, 0.000)—is statistically significant with respect to the reaction time. Similarly, the difference between dual-difficult condition (D6) and the rest of the conditions—single (S5,  $p=0.004$ ), dual-easy (D4,  $p=0.007$ ), and dual-moderate (D5,  $p=0.007$ )— is statistically significant with respect to the accuracy. Factors that might affect the reaction time for the phone alert is device acquisition time. Time to acquire the phone from the pocket is measured by collecting the brightness of the light received by the camera on the Motorola E680i phone. While the participant perceives and responds to the incoming alert on the phone, the changing light level is collected with time stamps for each event shown in Table 17. This technique is the same as the one used in the similar study that explored the device acquisition time of mobile phones [2].

I define the time between each event in Table 17 as follows:

- Pocket time: Between events 1 and 2
- In-hand answer time: Between events 2 and 3
- Replacement time: Between events 3 and 4

Visual distraction was not correlated with pocket time, in-hand answer time, or replacement time as determined using a one-sample t-test on the correlation coefficients relating the results of each condition and the visual task difficulty level. The average time from event one to event four is 3.89 seconds. The average pocket time, in-hand answer time, and replacement time is 1.68 seconds (43.11%), 0.94 seconds (24.10%), and 1.28 seconds (32.79%), respectively (Figure 49). The reaction time of the phone alert perception is the sum of pocket time and in-hand time. Figure 50 shows the high cost of device acquisition time across all conditions.

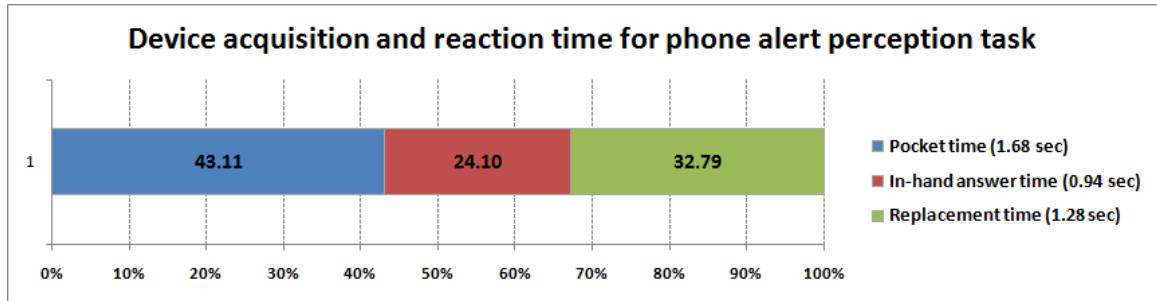


Figure 49: Interaction time for phone alert perception task.

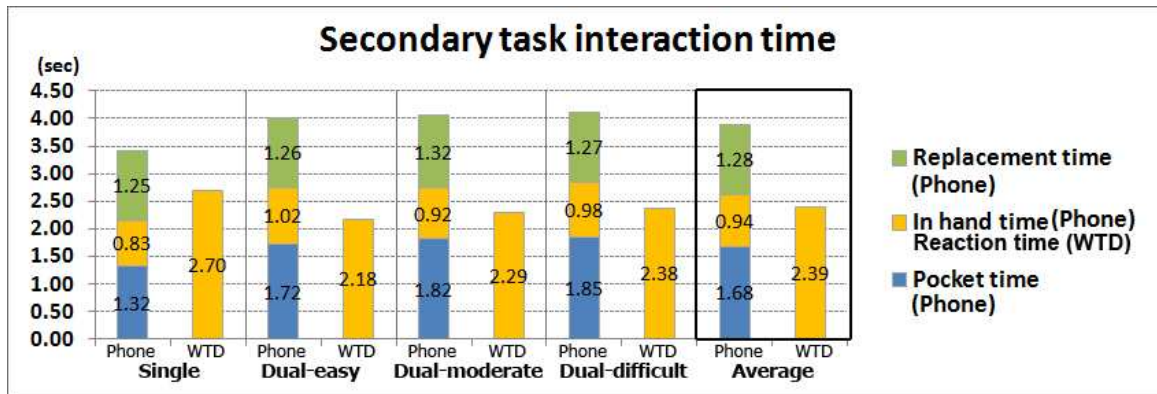
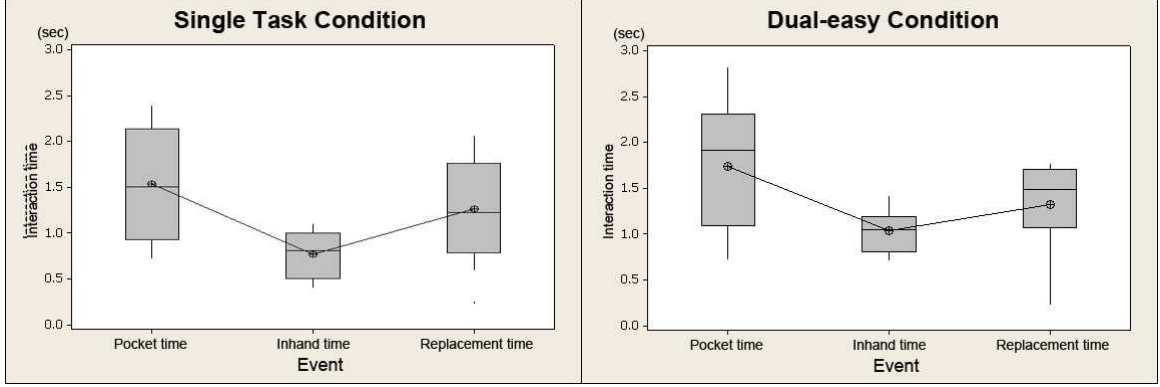


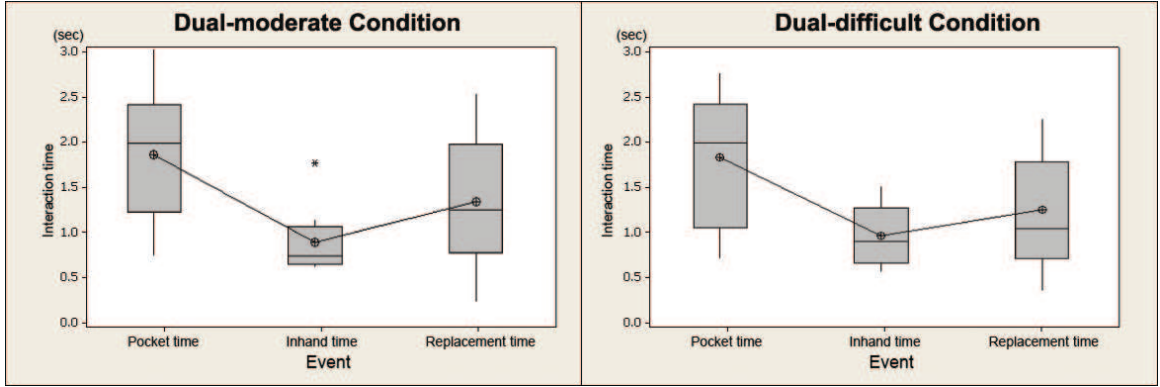
Figure 50: Interaction time for secondary task.

When comparing single task (secondary task only) and dual task (secondary task with easy, moderate, and difficult visual search task) conditions, the effect of distraction is not statistically significant in any of the interaction times using paired t-tests ( $p > .05$ ). However, the difference among the three interaction times (pocket time, in-hand time, replacement time) is statistically significant in all four conditions (Figure 51 & Figure 52,  $p < .05$ ). This result indicates that the temporal cost of pocket time and replacement time is higher than in-hand time, and these costs are relatively constant whether the alert perception task is distracted by the visual search task or not.

The information transfer rate (bits/sec) for the WTD in the most distracted condition (D3: dual-difficult condition) is even higher than the performance data obtained from the condition without distraction (S4: single task condition). The bits/sec for S4 and D3 are 0.56 bits/sec and 0.58 bits/second, respectively. This number indicates that although the user is interrupted continually with a high level of visual distraction, the information



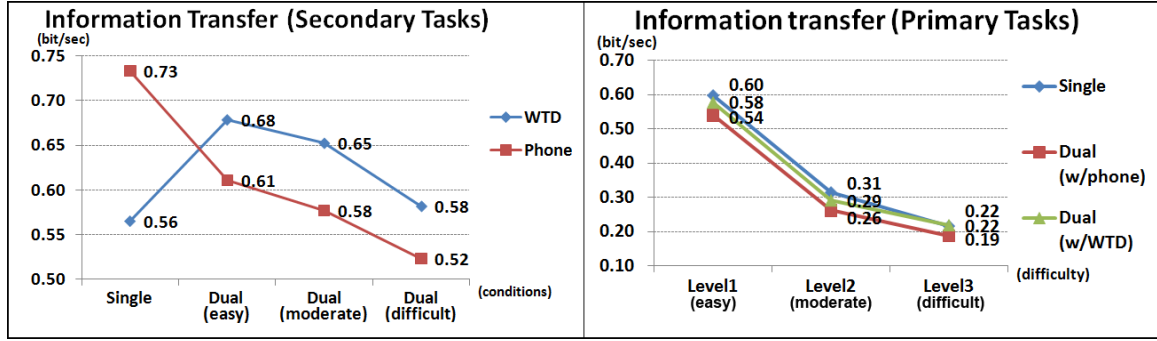
**Figure 51:** Interaction time for secondary task: Single (left) and Dual-easy condition (right).



**Figure 52:** Interaction time for secondary task: Dual-moderate (left) and Dual-difficult condition (right).

transfer is not deteriorated relative to the single task condition (Figure 53, left). The average bits/second in perceiving the tactile alert from the WTD from single and dual task condition is 0.56 bits/second and 0.64 bits/second, respectively.

However, the information transfer rate in perceiving alerts from the phone decreases constantly as visual task difficulty is increased. The average bits/second in perceiving the alert from the phone in single and dual task condition is 0.73 bits/second and 0.57 bits/second, respectively.



**Figure 53:** Information transfer: Secondary task (left), primary task (right).

### 5.6.2 Primary task: accuracy, reaction time, and information transfer rate

When comparing the single task (S1, S2, and S3 in Table 14) and dual task (D1, D2, D3, D4, D5, and D6 in Table 14) conditions, the effect of distraction that is caused by the phone alert perception is statistically significant in all difficulty levels (right column in Table 18) with respect to reaction time as determined by paired t-test ( $p < .05$ ). However, the effect of tactile alert perception through the WTD is not statistically significant with respect to reaction time of the primary task (left column in Table 18). The effect of the both secondary tasks with regard to the accuracy is not statistically significant as determined by paired t-test.

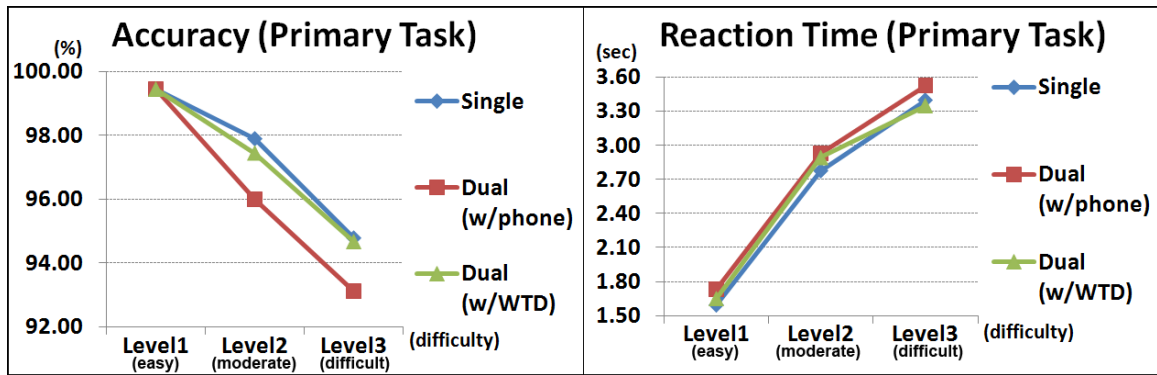
Participants reported that they preferred to finish the primary task when the secondary task triggered while they were still performing the primary task. Potentially the WTD and phone did not affect the primary task because the subjects prioritized the primary task as a strategy to manage the multitasking situation. The subjects' preference shows that although the loading-task technique was guided (Figure 10-right), the subjects tended to select a secondary-task technique (Figure 10-left). More detail will follow later.

The effect of difficulty (levels 1, 2, and 3) in the visual task was significant in accuracy (Figure 54, right, Figure 55, right,  $p < .01$ ) and reaction time (Figure 54, right, Figure 55, right,  $p < .01$ ) in all conditions in Figure 54 (single task, dual task with a phone, dual task with a WTD) using a one-way ANOVA.

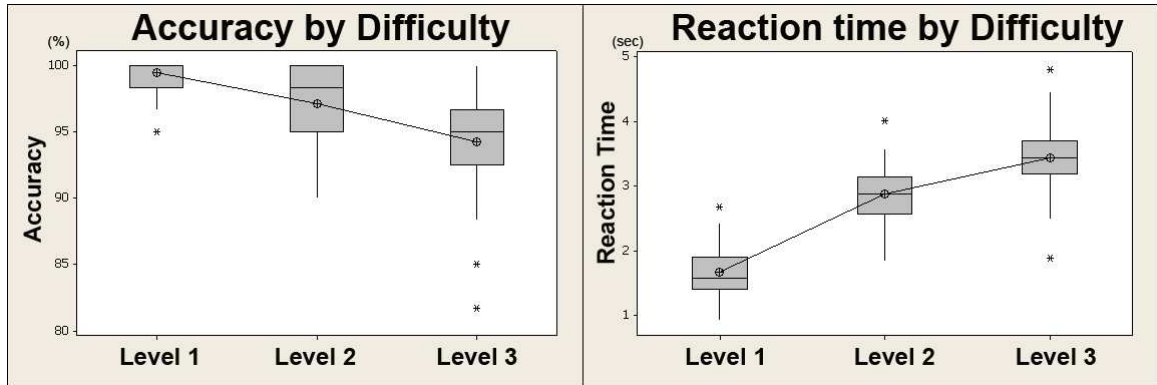
The information transfer rates for difficulty levels 1, 2, and 3 when distracted by the phone alerts were 0.54 bits/second, 0.26 bits/second, and 0.19 bits/second, respectively.

**Table 18:** P value of paired t-test with respect to reaction time in primary task (numbers in parentheses indicates the condition ID that is defined in Table 14): Top (Difficulty level = easy), Middle (Difficulty level = moderate), Bottom (Difficulty level = difficult).

Difficulty level = easy		
	Dual-easy-WTD (D1)	Dual-easy-phone (D4)
Single-easy (S1)	0.052	0.000
Difficulty level = moderate		
	Dual-moderate-WTD (D2)	Dual-moderate-phone (D5)
Single-moderate (S2)	0.126	0.005
Difficulty level = difficult		
	Dual-difficult-WTD (D3)	Dual-difficult-phone (D6)
Single-difficult (S3)	0.451	0.021



**Figure 54:** Primary task: Accuracy (left), Reaction time (right).



**Figure 55:** Performance of primary task by difficulty: Accuracy (left), reaction time (right).

These numbers slightly increased to 0.58 bits/second, 0.29 bits/second, and 0.22 bits/second when alerts were delivered by the WTD (Figure 53-right).

**Table 19:** Structure of workload assessment: M = mental demand, P = physical demand, T = temporal demand

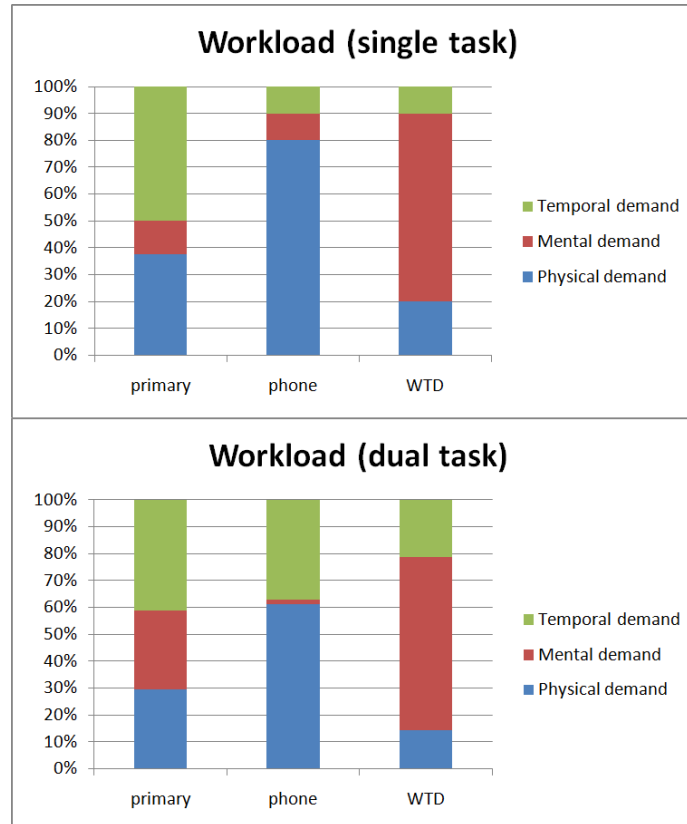
	Primary			Secondary (WTD)			Secondary (Phone)		
Single	M	P	T	M	P	T	M	P	T
Dual	M	P	T	M	P	T	M	P	T

### 5.6.3 Workload assessment and strategy to manage dual tasks

The mental, physical, and temporal demand to perform the primary task and the two types of secondary task both in the single and dual task conditions (Table 19, Figure 56) are explored during the post session using a modified NASA-TLX and a semi-structured interview. Participants are asked to note the overall difficulty and their opinion with regard to each cell in Table 19, as well as to order the three types of demand from the easiest to most difficult.

#### 5.6.3.1 Workload and strategy in primary task

Participants reported that temporal workload was the most dominant factor in the primary task due to the five-second time limit for each trial. The stress derived from the limited duration of each trial seems to affect their strategy in prioritizing the primary task during the dual task conditions subjects. When people needed to process the primary and secondary task at the same time in the dual task condition, they tended to prioritize the primary task rather than the secondary task. In this case, the secondary task was temporarily set aside and performed later. Compared to the single task condition, mental workload increased in the dual task conditions particularly when the difficulty level was high (Level 3). Participants reported that they needed to think about the appropriate strategy for prioritizing the tasks and deciding the moment to shift their attention from one task to another. Physical workload such as fatigue in the eyes and legs was observed when performing the primary task in both single and dual task conditions.



**Figure 56:** Workload of primary and secondary task: Single task (left), dual task (right).

#### 5.6.3.2 Workload and strategy in secondary task (Phone)

Physical workload was the most dominant factor with the phone alert system both in the single and the dual task conditions due to the need to shift visual attention. Mental workload was rarely observed either in single or dual task conditions with the phone alert condition. However, some participants reported that they needed to put extra thought in deciding the right time to acquire and restore the phone during the dual task condition.

#### 5.6.3.3 Workload and strategy in secondary task (WTD)

Mental workload was the most dominant factor in tactile alert perception with the WTD, both in the single and the dual task conditions. Five different types of mental models were observed from 16 participants when mapping the spatial configuration between the triangular motor layout and linear keypad layout that is associated with the numeric labels (1, 2, and 3). More detail will be discussed later in this chapter and Chapter 6. Although

participants performed the task with their own preferred mental model, they still reported that matching these two different concepts was difficult. The sequential movement of the stimuli with the WTD contributes to reducing the temporal workload. Even though the participants failed to perceive the first locus in the pattern, the consecutive loci of the remaining two motors guided them in determining the starting point.

#### **5.6.4 Summary**

When perceiving alerts through a WTD, the accuracy is not affected by visual distraction. However, the reaction time becomes faster when a small amount of visual distraction is added. This result suggests that WTDs can ensure safer alert perception in the real world where different levels of visual distraction exist during the course of mobile interaction (e.g., driving a car). On the other hand, perceiving alerts through a mobile phone is affected by the visual distraction both in accuracy and reaction time. In the reaction time for the phone alert perception, access time is observed as the critical factor. Pocket time and replacement time to acquire the device took longer (66%) than the in-hand answer time (34%). The visual search task was not affected by the WTD both in reaction time and accuracy. However, phone alert perception affects the visual search task with respect to reaction time. This result suggests that the current practice of receiving an alert from a mobile phone can increase a user's reaction time for visual tasks (e.g., searching for a street number while on-the-go).

Different types of workload were observed across the tasks: temporal workload for the visual search task, mental workload for the alert perception task using the WTD, and physical workload for the alert perception task using the phone. Due to the temporal workload of the primary task (five-second time-out per trial without a break between trials), people tended to prioritize the primary task.

### **5.7 Discussion**

The main purpose of this experiment was to explore the appropriateness of tactile alert perception through WTDs while visual distraction exists. The experiment in this chapter focuses on observing the effect of the visual distraction on WTDs and mobile phones rather



than direct comparison between the two. Due to the difference between WTD and current practice in modality, form factor, and previous experience, the appropriateness of the WTDs should be addressed with additional factors that are related to a real world context.

### 5.7.1 Mobile multitasking in the wild

As observed in the experiment in this chapter, one of the disadvantages of most handheld mobile devices, which are generally stored in the pocket or the purse, may be the mandatory requirement of access time.

The usability of mobile devices for on-the-go users is highly dependent upon the appropriate management of attentional and motor resources. Managing attentional and motor resources while on-the-go often requires immediate moment-by-moment decision making. When a mobile phone rings, blinks, or vibrates at an unpredictable moment, the strategy the user utilizes to prioritize one task over the other varies from situation to situation. Users have different levels of experience and expertise with these situations, and their choices can lead to hazardous situations.

Note that the initial motivation to develop the WTDs was to design a novel alert system for mobile devices that is less affected by visual distraction. One of the stories told by a participant during the post interview session suggests how the WTDs can contribute to easing problems in mobile interaction:

*“My aunt had a serious accident when she tried to answer a phone call while driving. While driving, she used to put her cell phone and the earphone on her lap. When she received a phone call at an intersection she did not have a problem finding the earphone to put in her ear. The accident happened when she moved her visual attention to her lap for a moment to find the call button on the phone. She could not see the other car and all people in the car were seriously injured.”*

As observed in this story, losing visual attention even for a short moment of time is problematic and may threaten the safety of on-the-go users. Although the shift of visual attention was not measured in the experiment, the workload assessment suggested that physical workload (e.g., taking the phone from the pocket and shifting visual attention

between the primary and the secondary task) and accompanying distraction were the major challenge of the phone alert. In addition, the distraction caused reaction time to deteriorate.

On the other hand, when perceiving incoming alerts from the WTD, for which no workload for device acquisition is assumed, the reaction time was not negatively affected by visual distraction. As already shown by a similar study that measured the relationship between task difficulty and engagement [41], I observed that visual distraction does not decrease perception speed but rather increases the speed, possibly due to an increase in engagement. Although participants reported that mental workload is the major challenge when perceiving alerts from the WTD, based on the result of the study, I hypothesize that this mental workload can be alleviated to some extent by practice with the WTDs.

Multitasking behavior in daily interactions varies from person to person. Some participants reported that multitasking while on-the-go is unsafe, inefficient, and impolite. However, other participants reported that multitasking while on-the-go helps save time and is becoming more and more ubiquitous these days.

*“I frequently read, look on my iPod and walk home. When crossing the street, I look up. Sometimes I run into trouble with cars leaving parking lots. I know it is not safe, but I won’t stop using my iPod while I’m on-the-go.”*

As is observed from this example, people who already know or have even experienced the unsafe nature of mobile multitasking were still inclined to interact with mobile devices while on-the-go on a daily basis. Note that as the users need to consume up-to-date services and applications using today’s mobile devices, augmenting the safety of on-the-go users by using WTDs is a promising way to support increasingly ubiquitous mobile interaction.

The asymmetric mental model of matching three motors in the WTD with three buttons in the keypad is one of the limitations of the study. Participants reported that they had to spend extra time to match what they felt on the skin with what they pressed on the keypad. Thus, I hypothesize that the reaction time to perceive alerts from the WTD could be faster if the keypad is configured with a triangular shape or if the performance is assessed longitudinally.

Although this study focuses on controlled visual distraction only, distraction in the wild

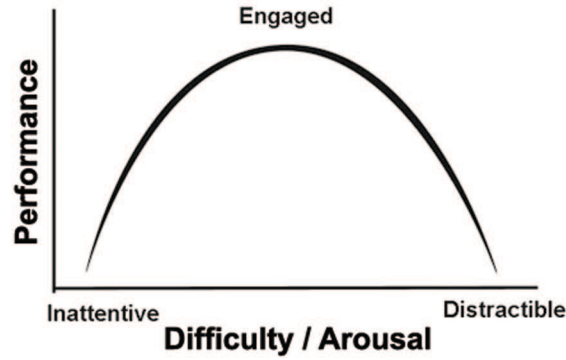
can be richer, more complicated (e.g., ambient noise, presence of other people in a public space, motor demand for walking or holding bags, etc.), and less controllable. Based on the results of this study, adding and evaluating the effects of other distractions would help to explore the benefit and limitations of WTDs for mobile multitasking in the wild.

### **5.7.2 Attention and engagement: Yerkes-Dodson Law**

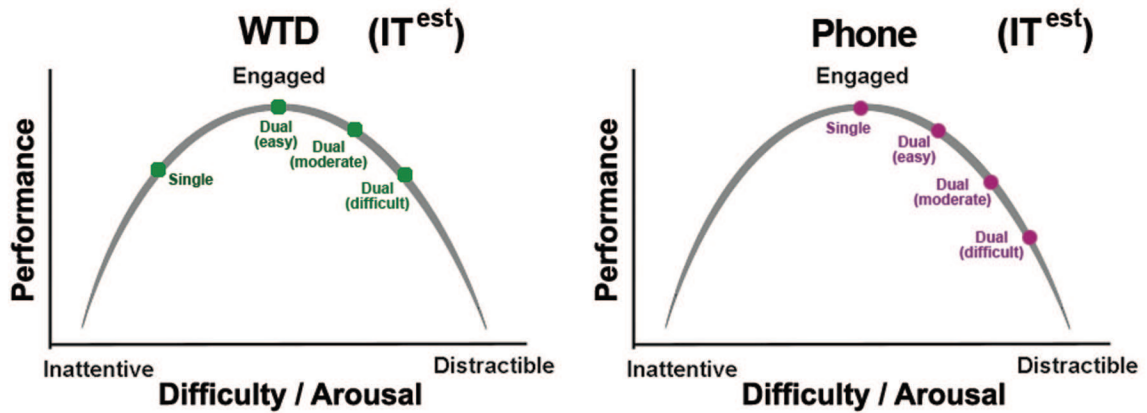
The effect of light visual distraction (level 1 primary task) on the reaction time for the secondary task was different between the two devices (Figure 48, right). Although the effect of engagement, stress, and emotion is not measured in the experiments, the different effect implies that the difficulty of the primary task was perceived differently between the two devices.

According to the Yerkes-Dodson Law, human performance decreases when difficulty is too low (inattentive) or too high (distractible) [132]. On the other hand, a medium level difficulty maximizes performance by generating optimal arousal and engagement (Figure 57). Thus, I suspect that the difficulty with light visual distraction was too high for the phone (distractible) and moderate with the WTD (engaged). Specifically, with light visual distraction (level 1-easy), the perceived difficulty of the phone alert changes towards a distractible level that results in a slower reaction time (Figure 58, right) whereas the perceived difficulty of the tactile alert changes toward an engaged level that results in a faster reaction time (Figure 58, left). Such levels of engagement were observed anecdotally during the experiment. While performing the single task with the WTDs, several participants reported that they were thinking about something else during the experimental session because the task was boring.

As already suggested by a similar study that measured the relationship between task difficulty and engagement [41], I observed that a small amount of visual distraction was still manageable in perceiving tactile stimuli from the WTD and increased performance. However, since the second experiment was performed in a controlled lab setting, the external validity of this result in the real world situation is unclear. Thus, to generalize this result, future studies that explore the benefits of the WTD in more natural conditions are required.



**Figure 57:** The relationship between performance and perceived difficulty: Yerkes-Dodson Law (adapted from Yerkes and Dodson [132]).



**Figure 58:** Yerkes-Dodson Law in the two secondary tasks: WTD (top), phone (bottom).

### 5.7.3 Attention and information processing: automatic and controlled processing

The participants' reported strategy to prioritize the primary task in the dual task condition implies that they employed selective attention to manage their attentional bottleneck. Given Shemacher's study [106] on practice and simultaneous performance of dual tasks, I suspect that this selective attention paradigm may be changed to a divided attention paradigm with further training. In the selective attention paradigm, the costs are mainly dependent upon the types of information processing: automatic and controlled processing [54].

Automatic and controlled processing have been studied in psychological research for over a century. The definition of the two processes [104] is mainly determined by the familiarity

and consistency of the tasks that the user needs to process.

*Automatic processing* refers to a task which is familiar and consistent such that it “nearly always becomes active in response to a particular input configuration” and that it “is activated automatically without the necessity for active control of attention by the subject.”

On the other hand, controlled processing is observed when performing unfamiliar and inconsistent tasks. *Controlled processing* refers to “a temporary sequence of nodes activated under control of, and through attention by, the subject.” Controlled processes are “tightly capacity limited, but this capacity limitation is balanced by the benefits deriving from the ease with which such processes may be set up, altered, and applied in novel situations for which automatic sequences have never been learned.”

Unlike controlled processing, automatic processing can bypass attentional bottlenecks [105]. In the secondary task configuration of the experiment in this chapter, the alert perception using the WTD, which is novel and requires an additional workload to construct a mental model of operation, was probably controlled processing, whereas the alert perception using the mobile phone, which is already well-established through daily use, could be automatic processing. Despite this disadvantage in processing attentional phenomena, the  $IT_{est}$  in perceiving incoming alerts is higher with the WTD than with the mobile phone.

I hypothesize that performance could increase with the WTD in the single and the dual task conditions as the task becomes more automatic. Since the participants reported that the mental workload in receiving alerts with the WTD was problematic, automatic processing might be facilitated by improving the system (e.g., providing a consistent spatial mapping between the motor and the keypad) and by practice. However, this improvement would be surprising with the mobile phone because the performance is mainly limited by the inherent motor constraints and inefficient time-sharing of visual attention between the two tasks.

### **5.8 Mental workload for spatial mapping**

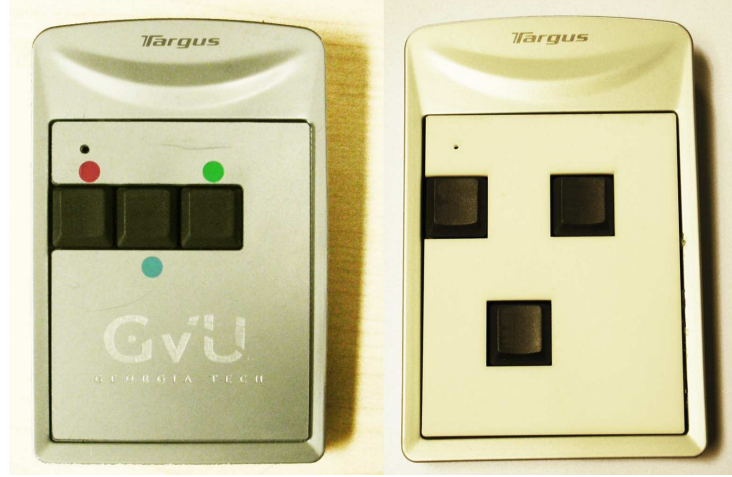
During the test at the Georgia Institute of Technology, a limitation of the study design was observed. As discovered from the interview in the previous section, the different topological

mapping between the triangular layout of the motors and the linear layout of the keypad generated additional workload when the participants needed to match the tactile stimulation with a motor response. Assuming that this limitation more or less affected the result of the previous section, additional studies that explore the effect of the additional mental workload were performed. The research question and hypothesis of this section is described as follows:

**Research Question 2-verification** : Is the performance to perceive the tactile pattern on the wrist improved if the topological mapping between stimulus and response is more similar?

**Hypothesis** : Yes, a more similar topology between the tactile pattern and the keyboard layout for response reduces the workload of the participants.

In these additional studies, participants were divided into two groups. One group (Group A) of participants performed the alert perception tasks with the old keypad with the linear layout identical as in the original experiments (Figure 59-left), and the other group (Group B) of participants performed the same task with the new keypad with a triangular layout (Figure 59-right). The performance of Group A is compared with the performance of the original experiment that was performed in the previous section to see the external validity of this verification. The performance of Group B is compared with Group A to explore how much the performance can be improved with the modified keypad design. To perform the experiment in this section, 18 participants were recruited from the Electronics and Telecommunication Research Institute (ETRI). Out of 18 participants, six participants performed the task as Group A and 12 participants performed the task as Group B. However, the data for one participant from Group A and three participants from Group B is excluded for analysis because the experiment was not conducted as guided. The study was performed in a quiet lab setting in ETRI. The mean age of Group A (five participants, four male, one female) and Group B (nine participants, eight male, one female) is 36.80 and 33.56 years, respectively. The mean age of Group A (36.80 years) is 10.11 years older than the participants of the previous section who are recruited from Georgia Institute of Technology (GT participants, 26.7 years).



**Figure 59:** Two types of keypad: linear layout for Group A (left), triangular layout for Group B (right).

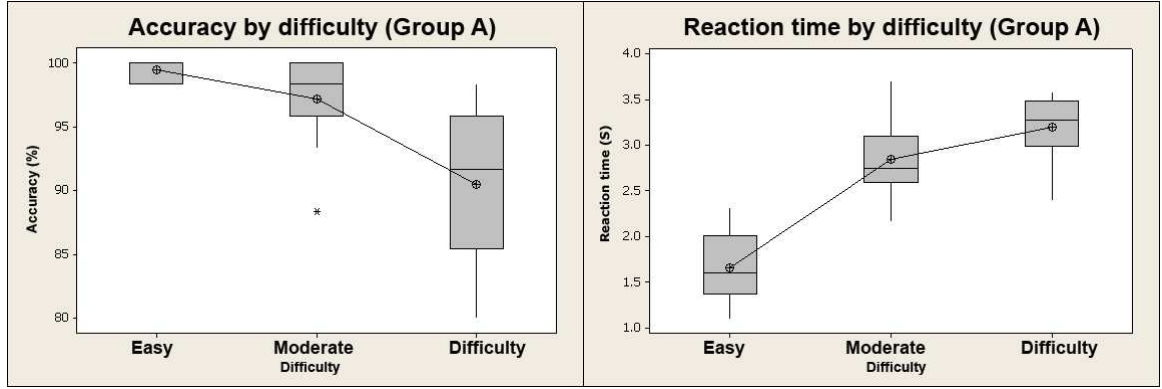
**Table 20:** Conditions and tasks in verification (Numbers in parenthesis indicates the number of trials for each task in each condition): L1=level 1 (easy), L2=level 2 (moderate), L3=level 3 (difficult), W=WTD

	Single task				Dual task		
ID	S1	S2	S3	S4	D1	D2	D3
Primary	L1 (60)	L2 (60)	L3 (60)	- -	L1 (60)	L2 (60)	L3 (60)
Secondary	- -	- -	- -	W (3×5)	W (3×5)	W (3×5)	W (3×5)

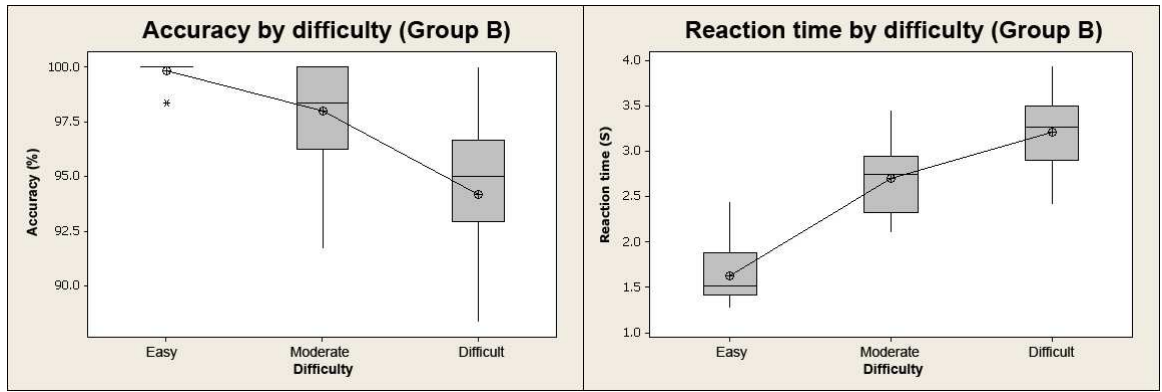
The study setting is identical to the original experiments. The conditions for the new experiments are explored in Table 20. As a secondary task, only the alert with the WTDs is explored in this study.

### 5.8.1 Result: Secondary task

The difference between Group A and Group B is not statistically significant in any of the four conditions (single, dual-easy, dual-moderate, or dual-difficult) in accuracy, reaction time and bits/second as determined by paired t-tests ( $p > .05$ ). Similarly, when comparing Group A participants and GT participants, the difference in accuracy, reaction time, and bits/second between these two groups are not statistically significant in any of the four conditions as determined by paired t-test ( $p > .05$ ).



**Figure 60:** Accuracy and reaction time by difficulty of primary task in Group A.



**Figure 61:** Accuracy and reaction time by difficulty of primary task in Group B.

### 5.8.2 Result: Primary task

In all six conditions (single-easy, single-moderate, single-difficult, dual-easy, dual-moderate, and dual-difficult), the effect of using the different keypads is not statistically significant in accuracy, reaction time, or bits/sec based on t-tests.

Similar to the previous experiment at the Georgia Institute of Technology, the effect of difficulty level (easy, moderate, difficult), as reported by a one-way ANOVA, is statistically significant in accuracy, reaction time, and information transfer rate (bits/second) on both Group A and B ( $p < .01$ , Figure 60 and 61). On the other hand, the effect of distraction is not statistically significant between the single and dual tasks for either Group A or Group B for accuracy, reaction time, or bits/sec based on one-way ANOVA.

When comparing Group A participants and GT participants, a consistent trend is not



observed in the conditions in general. The difference of accuracy, reaction time, and bits/sec between these two groups are not statistically significant in any of the six conditions using a t-test.

### **5.8.3 Discussion**

The effect of additional workload associated with the inconsistent topology between the motor layout for perception and the keypad layout for response is not statistically significant in general. The performance of Groups A and B consistently decrease from single to dual-difficult conditions.

## ***5.9 Summary of the chapter***

As I hypothesized early in this chapter, the alert perception through WTDs, in which the reaction time becomes slower only with the large amount of visual distraction, is less distracted by the visual distraction than the mobile phone. Similarly, WTDs distracts the visual search task less compare to mobile phone. Compared to the mobile phone that is consistently affected by the visual distraction both in reaction time and accuracy, this result indicates that alert perception through WTDs can be a suitable method to deliver alerts for on-the-go users who are engaged with visually.

When people perceive alerts from the WTD, a small amount of visual distraction (easy level) facilitates more engagement and results in faster reaction time than the single task condition without distraction. The performance of the primary task is affected by the difficulty level and distraction caused by the phone alert perception. However, the alert perception through the WTD does not affect the primary task. This result is consistently observed in the ETRI experiment.

## CHAPTER VI

### SUBJECT BEHAVIOR AND PHYSIOLOGY

This chapter presents additional survey information that was collected while performing experiments in Chapter 4 and Chapter 5.<sup>1</sup>

#### **6.1 *Preliminary survey***

Forty-seven people participated in the survey that measured wrist size and wristwatch wearing behavior. This survey was conducted with 31 students attending the Georgia Institute of Technology (USA) and 18 researchers at the Electronic and Telecommunication Research Institute (South Korea). Among these participants, 34 people answered the survey that assayed daily mobile phone carrying behavior. Since all participants were observed to be right-handed when interacting with computers, data using WTDs in this chapter is limited to the left, or non-dominant, hand.

##### **6.1.1 Wrist measurements**

The width and circumference of the left wrist of 47 people (34 male, 13 female, mean age 30.57) was measured (Table 21 and Table 22). The average width of the male and female left wrist was 57.39mm (SD=2.89, min=49.1, max=62.0) and 51.34mm (SD=5.28, min=46.1, max=56.5), respectively. The average circumference of the male and female left wrist was 167.15mm (SD=8.90, min=142, max=180) and 147.92mm (SD=7.88, min=135, max=159), respectively. For both male and female participants, Caucasian participants have slightly bigger wrist widths and circumferences than those of Asian participants.

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<sup>1</sup>Parts of this chapter have been published in ACM SIGCHI Conference on Human Factors in Computing Systems (CHI) [67, 69] and ACM SIGCHI Conference on Human-Computer Interaction with Mobile Devices and Services (MobileHCI) [70].

**Table 21:**

Width and circumference of the left wrist of male subjects in mm (second row indicates number of participants)

	<b>Male</b>		
	Asian (22)	Caucasian (12)	All (34)
Width	56.7 (SD=2.7)	58.7 (SD=2.9)	57.4 (SD=2.9)
Circumference	165.2 (SD=8.4)	170.8 (SD=9.0)	167.2 (SD=8.9)
Age	32.9 (SD=5.0)	27.3 (SD=9.5)	30.9 (SD=7.3)

**Table 22:** Width and circumference of the left wrist of female subjects in mm (second row indicates number of participants)

	<b>Female</b>		
	Asian (10)	Caucasian (3)	All (13)
Width	50.3 (SD=3.5)	51.60 (SD=2.1)	50.57 (SD=3.2)
Circumference	147.0 (SD=8.7)	151.0 (SD=3.6)	147.9 (SD=7.9)
Age	31.6 (SD=5.0)	23.3 (SD=2.5)	29.7 (SD=5.8)

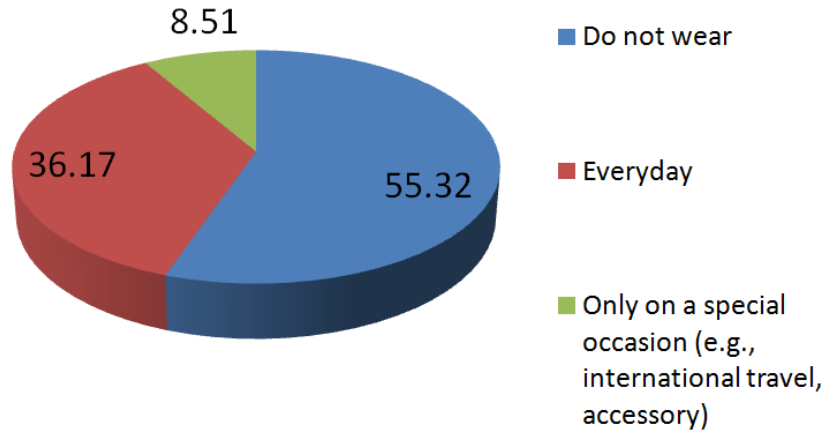
### 6.1.2 Wristwatch wearing behavior

I surveyed the subjects to determine if they wore a wristwatch or bracelet in their daily life (34 male, 13 female, mean age 30.57 years, Figure 62). 36.17% of people wore a wristwatch on a daily basis. 8.51% of people wore a wristwatch only on a special occasion (e.g., international travel, as an accessory, etc.). 55.32% of people answered that they did not wear a wristwatch or a bracelet at all. These subjects were asked the reason they did not wear a wristwatch on a daily basis (Figure 63). 50% answered that they did not like a wristwatch for various reasons (e.g., irritation due to sweating or the watch's tightness). 33.33% of those surveyed answered that they did not need a wristwatch because their mobile phone showed the time. 16.67% answered that they wear a wristwatch only on a special occasion (e.g., fashion accessories).

### 6.1.3 Mobile phone carrying behavior

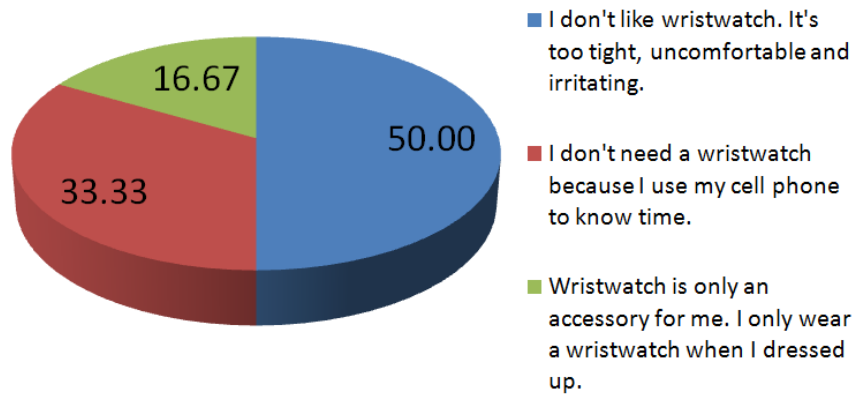
Thirty-four subjects (24 male, 10 female, mean age 31.44 years) were asked about how they tend to carry their mobile phone. A gender difference was observed in the results. Most of

### How often do you wear a wristwatch (%)



**Figure 62:** Survey of subjects' habits for wearing wristwatches.

### Why do you not wear a wristwatch? (%)

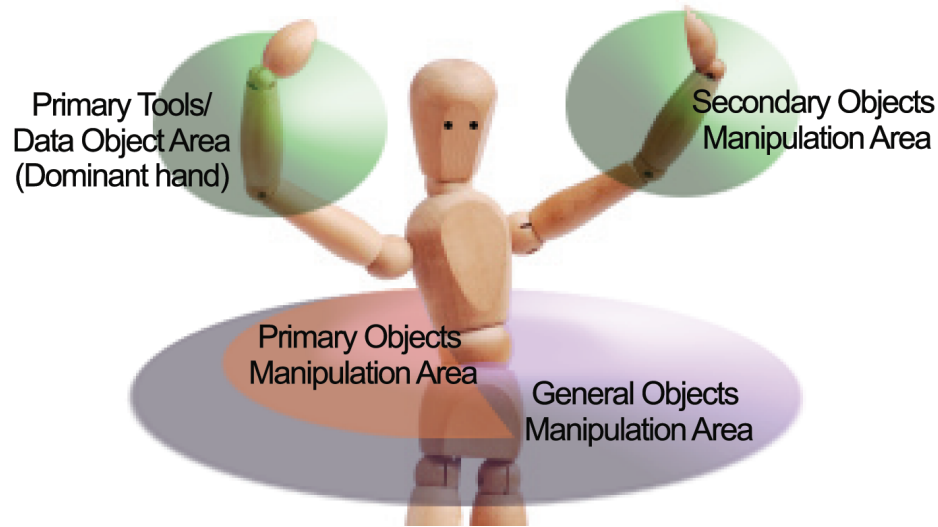


**Figure 63:** Survey of subjects' reasons not to wear wristwatches.

the male participants carry their mobile phone in their pocket (95.83%) rather than in a purse (4.17%). However, most of the female participants carry their mobile phone in their purse (80%) instead of their pocket (20%).



**Figure 64:** Various spatial configurations of hands during everyday mobile interactions (e.g., driving a car, riding a bicycle, holding objects).



**Figure 65:** Body configuration of right-handed users when managing near-body information (adapted from Biocca et al. [6]).

## 6.2 Construction of mental model to label spatial tactile patterns on the wrist

In Chapter 5, all subjects recruited from the Georgia Institute of Technology (GT participants) and Group A subjects recruited from ETRI needed to map the tactile pattern to the three keys on the keypad in order to respond. This section explores the different mental models subjects created to perform this task. Although this dissertation does not focus on the coupling of tactile stimulation with meaning, I assume the factors discovered when the participants constructed their mental models may provide important lessons for future work.

### 6.2.1 Mental model construction in perceiving tactile patterns

In the design of wearable interfaces, understanding the human body as a design space is critical. For example, when the interface is worn near the hands, its spatial orientation can be highly variable due to the many degrees of freedom of movement allowed by the shoulder, elbow, and wrist (Figure 64). When manipulating physical or virtual objects in a mobile interaction, users organize information spatially around the body and configure their body so as to simplify the task (Figure 65, [6]). Here, I assume that this tendency applies similarly to interfaces based on touch.

Because body parts can be twisted, rotated, and tilted, the X-Y axis coordinates of the tactile display can be interpreted in various ways. For example, a directional tactile pattern that is perceived to move from left to right on the wrist when the user places her forearm vertically with the palm facing toward herself is perceived as a pattern in the opposite direction when she holds the palm facing away. Thus, it can be difficult even to describe a pattern when attempting to assign it an abstract meaning.

A parallel topic to information visualization, information tactilization refers to the presentation of abstract information that is perceived through the sense of touch [13]. An intuitive mapping between a tactile stimulus and the real world information it represents is highly recommended in designing an easy-to-learn and self-revealing tactile information system [121, 77]. However, to increase the number of “words” in a tactile vocabulary, what should be considered in the design of directional patterns for everyday mobile interaction, where the body’s geometry changes frequently (Figure 64)?

### 6.2.2 Factors in mental model construction

During the practice session for the experiment presented in the last chapter, both GT participants and ETRI participants in Group A (15 males, 7 females, mean age 29.77 years) were asked to match three motor positions with three numbers (1, 2, and 3). Mapping the motor location with the numeric representation was required to match the position of the motors with the number keys in the keypad. A piece of paper with three blank circles representing the reverse triangular layout was provided to initiate the construction of the

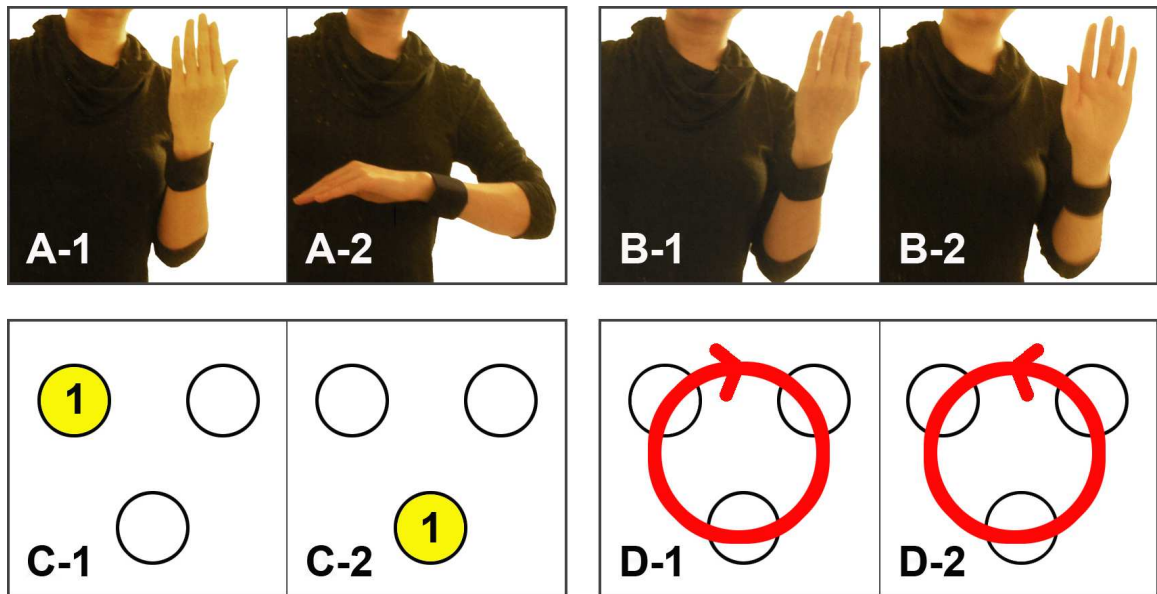
subject's mental model. The participant was asked to label each circle with a number ('1', '2', or '3'). The WTD with its three vibrating motors was shown to the participant to assist the labeling process. As a review, the WTD is mounted on the palm side of the wrist and has two vibrators mounted close to the palm and perpendicular to the wrist and one vibrator mounted further up the forearm toward the body. No information regarding the tactile pattern (e.g., moving direction for each pattern, or numeric symbols) was provided while the participant built her mental model. Once the participant presented and confirmed her labeling scheme, the WTD was worn on the non-dominant hand so as to reflect the mental model. While the participant stood, a randomly selected tactile pattern was generated on the wrist. The pattern was repeated until the participant pressed the corresponding number on the keypad reflecting the numeric label (using the dominant hand). The participant was allowed to change her labeling scheme if the previous scheme was not reasonable. Six trials (3 patterns x 2 times) were required. Additional trials were provided upon request.

After six trials, 20 participants completed their testing; two participants requested six more trials. Participants built seven types of labeling schemes (Figure 68) which were constructed using four factors (Figure 66 and 67):

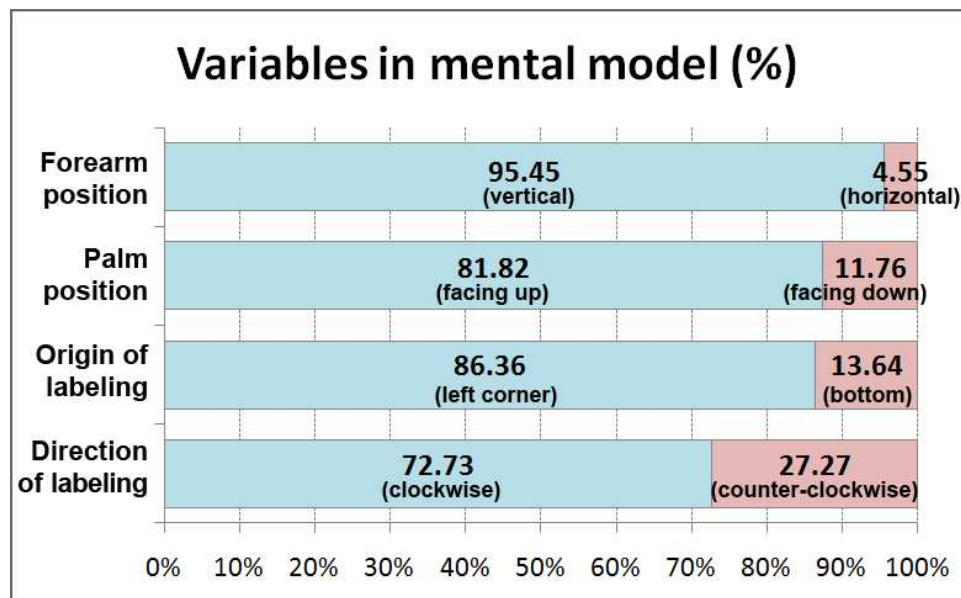
- Forearm position: vertical or horizontal
- Palm position: facing the palm towards or away from the body
- Origin for "1" label: left corner or bottom
- Direction for labeling: clockwise (CW) or counter-clockwise (CCW)

Two factors were observed regarding body posture: the forearm and palm position. 95.45% of the participants placed the forearm vertically (A-1 in Figure 66) and 4.55% placed the forearm horizontally (A-2 in Figure 66). With respect to the palm position, 81.82% placed the palm in (B-1 in Figure 66) while 11.76% placed the palm out (B-2 in Figure 66).

Another two factors, origin and direction of labeling, were observed. 86.36% of the participants assigned '1' to the left corner circle (C-1 in Figure 66) whereas 13.64% of the



**Figure 66:** Factors when constructing a mapping between tactile pattern and keypad: Forearm position (A-1: vertical, A-2: horizontal), palm position (B-1: palm in, B-2: palm out), origin (C-1: left corner, C-2: bottom), direction for labeling (D-1: CW, D-2: CCW).



**Figure 67:** Four factors and variables in building a mapping between pattern and keypad.



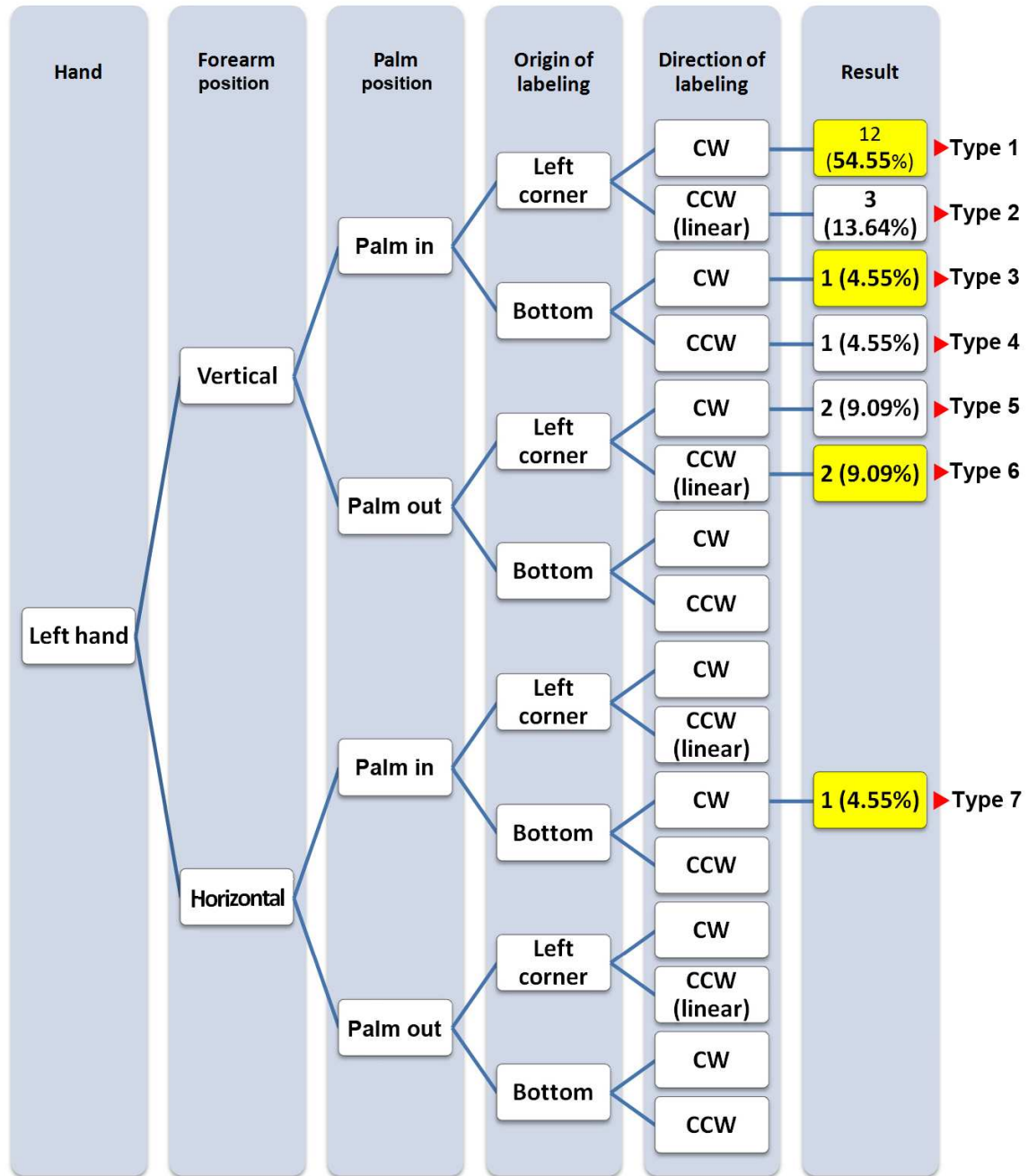
participants started labeling from the bottom circle (C-2 in Figure 66). With respect to the labeling direction, 72.73% of the participants proceeded labeling clockwise (D-1 in Figure 66) while 27.27% proceeded counterclockwise (D-2 in Figure 66). Figure 68 shows a tree with the four factors including the number and percentage of participants who chose each labeling scheme.

### 6.2.3 Design implications

In this experiment, participants had to match the direction that the tactile pattern moved to their label (D-1 and D-2 in Figure 66). The stimulation direction is counterclockwise when the palm faces in whereas the stimulation direction is clockwise when the palm faces out. For 72.73% of the participants (Type 1, 3, 6, and 7: yellow boxes in Figure 68), the stimulation and labeled direction would seem counter to each other if viewed from the eye point of the participant. Specifically, for these participants, two configurations occurred: placing the palm out (clockwise direction) while labeling the vibrators in a counterclockwise direction (4.55%, Type 6) and placing the palm in (counterclockwise pattern direction) while labeling the vibrations in a clockwise direction (67.88%, Type 1, 3, and 7). It is unclear whether these mismatches caused confusion.

22.73% of participants labeled the vibrators starting from the left corner and proceeding in a counterclockwise direction (Type 2 and 6 in Figure 68). However, it is unclear whether the direction was meant to be counterclockwise or simply moving linear to the right, which reflects cultural norms and the reading direction of the participants' first language (English and Korean).

The notion of heuristics and cultural norms may be especially important when designing for automatic processing in attentional performance [105] in everyday mobile interaction. For example, the location of the driver's seat and direction of the vehicle on the road in the US and the UK are different. Proficient management of such heuristics enables people to perform automatic interactions without paying attention to step-by-step procedures. Thus, in a mobile computing environment, where interruption is frequent and the cognitive cost of interaction is high, taking advantage of well-established heuristics is important to reduce



**Figure 68:** Tree of the participants' labeling schemes showing four factors. The WTD is worn on the left hand. The Result column presents the scheme (Type 1-7), the number and percentage of participants using that scheme, and whether there was inconsistency between the pattern direction and the labeling direction (yellow boxes).

attentional workload.

Several participants reported that they wanted to see the volar side of the wrist while performing tasks in all of the 11 conditions in the main Chapter 5 experiment even though

the actuators were fully covered by the strap. Although I did not explore this aspect in the study, the subjects' preference for a vertical forearm and palm facing in may have been affected by the side of the wrist (volar) that the vibrators were mounted. Thus, repeating the experiment with the WTD mounted on the dorsal (back of the hand) side of the wrist and observing people's preferences may be insightful in the future.

The layout of the triangularly-shaped pattern of vibrators might have also affected the selection of the forearm position. The two points in the top segment of the triangle (red and green actuators) are set parallel to the strap orientation across the wrist. Although this layout was selected to ensure better perception of the tactile patterns [83], it may have affected the construction of the participant's mental model. Interestingly, one of the participants who did not wear a wrist watch on a daily basis preferred to hold his hand as if looking at a watch while building his labeling scheme (Type 7 in Figure 68).

Participants created several types of labeling schemes that were much more sophisticated than expected when mapping three on-body tactile patterns to three symbols. The issues and limitations discussed in this section suggest some care may be necessary when attempting to encode information into tactile patterns.

## CHAPTER VII

### DISCUSSION AND FUTURE WORK

By necessity, the tactile display designs and experiments in the preceding chapters were limited in what issues they could address. This chapter explores other factors that might be considered in designing WTDs, tactile patterns, and user studies in this area. <sup>1</sup>

#### ***7.1 Design implications***

The recent release of mobile phones that provide user-customizable tactile alerts [12, 88] allows a richer mobile experience while possibly reducing visual distraction. The emergence of mobile tactile UIs indicates a desire for using the sense of touch for mobile interactions in addition to the visual and auditory channels. Various types of microinteractions, such as displaying the caller ID for an incoming phone call or SMS, can be supported by tactile UIs to reduce visual distraction. This dissertation provides results that can assist an interaction designer in selecting appropriate parameters for designing tactile patterns to support microinteractions in-the-wild with less visual distraction than current mobile alerts.

#### ***7.2 Expanding design variables in designing tactile displays and patterns***

Lessons learned from the experiments in Chapter 3 and 4 provide valuable guidelines to design robust tactile UIs by understanding limitations and capabilities of users. However, in this dissertation, a limited number of variables were selected and evaluated to improve the design of tactile displays and patterns (Table 23). Since those that were evaluated in this dissertation revealed only partial issues of the design, expanding the scope in various directions (e.g., stimulus length, display placement on the wrist, parameter configuration, ergonomics) is necessary to improve the system.

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<sup>1</sup>Parts of this chapter have been published in ACM SIGCHI Conference on Human Factors in Computing Systems (CHI) [27].

**Table 23:** Variables in design tactile displays and patterns

Profile	Tested variables	More variables
Stimulus length	500 ms, 1000ms	TBD
ISI (Inter-stimuli-interval)	100ms	TBD
Center-to-center distance	16mm, 30mm	TBD
Number of step	2, 4, 12, 16	TBD
Number of actuators	3, 4	TBD
Display placement on the wrist	Volar side	Dorsal side, two sided (volar and dorsal)
Types of display	Electro-tactile, vibro-tactile	Piezoelectric, etc.
Parameters configuration	Intensity, rhythm, direction, starting point	Frequency, waveform (frequency + intensity)
Ergonomics	None	Tightness, user-dependent placement for bone conduction

### 7.2.1 Stimulus length

In Chapter 3, I chose a 500 ms stimulus length based on a pilot study that compared 500 ms and 1000 ms durations. However, to explore the more precise limitations and capabilities of human tactile perception, more experiments should be done. Specifically, if the stimulus time can be minimized, the  $IT_{est}$  rate (bits/sec) can be maximized.

### 7.2.2 Display placement on the wrist

By utilizing both the volar and dorsal sides of the wrist in the design of tactile displays, the spatial real estate of the tactile pattern design can be expanded. Two-dimensional tactile displays that are arranged along the circumference of the wrist may enable three-dimensional tactile displays.

### 7.2.3 Parameter configuration

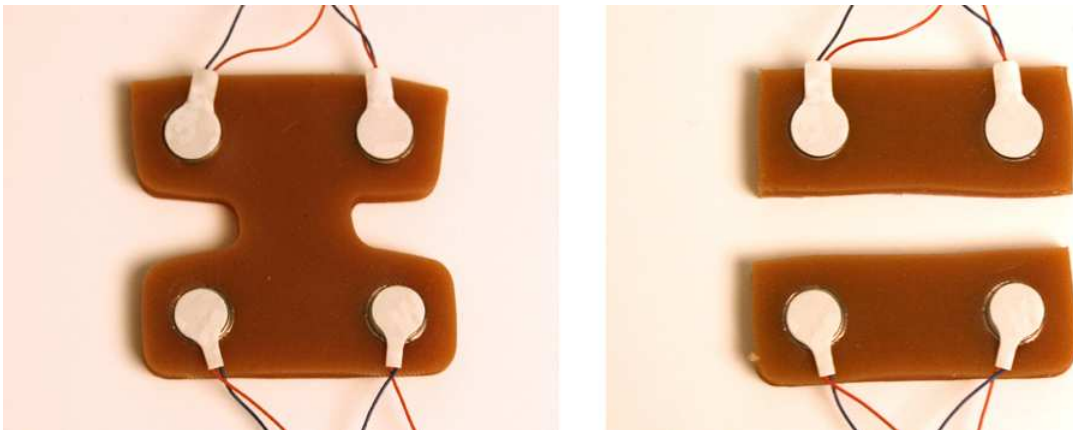
This dissertation evaluates only a few of the parameters involved in creating a tactile display. Although intensity was the most difficult parameter to distinguish, the difficulty might be reduced by changing the way intensity is presented. The ability to discriminate frequencies increases when they are presented in a relative way rather than an absolute way [9]. A

similar effect might occur with intensity. Anecdotally, there is some evidence for such an effect from the experiment in Chapter 4. Participants anecdotally reported that, for two consecutive patterns, perceiving changes in intensity was much easier.

Frequency generally affects the perceived intensity of a tactile pattern. Thus, it was not selected as a parameter for pattern design in this work to avoid possible confusion between frequency and intensity. However, a proper combination of intensity and frequency can augment the quality of tactile stimulation in a more distinguishable way through redundant coding.

#### 7.2.4 Ergonomic issues

Participants reported many ergonomics issues both with the electro-tactile and vibro-tactile displays. The major ergonomics issues involved maintaining appropriate contact and tightness between the display surface and the wrist. In the current implementation, although both regular and elastic wristbands were tested, no particular solution resolved the issue. Exploring various material and form factors for the wristband [27] is an area for future work.



**Figure 69:** Rubber housing of the tactile display: Partial separation between rows(left), Full separation between rows (right).

Since previous research [83] revealed that the vibro-tactile alerts *across* the back of the forearm (from thumb to pinky) are easier to perceive than *along* the back of the forearm (from wrist to elbow), separating the vibrators by row is more reasonable than separating them by columns. For my ongoing work I am using vibrators fully separated by row (Figure

69).

During the pilot study in Chapter 3, one of the participants reported an increased sense of intensity around the wrist bone which assisted him in localizing the actuators. Although the reason for the magnified intensity is unclear, exploring possible factors such as bone conducting vibration may provide an additional mechanism for improving tactile patterns on the wrist.

### **7.3 *Expanding research focus***

In addition to examining more of the design variables, future work should also examine more of the contextual issues involved in using tactile displays. Such an effort will help create a richer user experience during real world usage.

#### **7.3.1 Longitudinal study**

Experiments performed in Chapters 4 and 5 explored novice users' performance only. The high mental workload that was observed in Chapter 5 reflected that participants required extra time and effort to perceive alerts from WTDs. However, in spite of the high mental workload caused by the unfamiliarity of the system, the results in Chapters 4 and 5 are quite promising. With practice, users' workloads might diminish. A longitudinal study should show this effect as well as provide information on how users transition from novice to expert use of the system.

#### **7.3.2 Moving from tactile stimulation to tactile information**

The focus of this thesis has mostly been limited to the perception of the WTDs. However, the design of tactile information is not only limited to sensory perception but also includes the integration of attention, cognition, and learning when matching particular stimulation to meanings [121, 77]. Researchers have explored the design of various tactile patterns such as tactile icons or tactons [77, 14, 9] to transfer complex concepts and messages in mobile computing. Tactile icons are the tactile equivalent of visual icon or auditory earcon. Well-designed tactile icons should be easy to learn and memorize, able to carry meaningful contents, and intuitive to create a language of tactile interaction [95]. Exploring human

ability to match particular meanings to tactile stimulation is necessary in the future to reveal the benefit of WTDs.

### **7.3.3 Beyond visual distractions**

Experiments in Chapter 5 explore visual distraction as a representative of the most challenging factors of on-the-go interaction. By simulating real world distraction scenario, Chapter 5 proves the appropriateness of the WTDs that can contribute to ensure eyes-free mobile interaction. However, challenges in-the-wild can be more sophisticated. In addition to visual distraction, auditory or motor distraction in a mobile context can affect on-the-go interaction very frequently. Thus, based on the results of this thesis, exploring the effect of auditory and motor distraction in perceiving tactile alerts through WTDs and vice versa is still an opportunity to explore the benefits and limitations of WTDs in a more realistic scenario.

### **7.3.4 Beyond laboratory experiments**

In this thesis, all experiments were conducted in strictly controlled quiet laboratories. The benefit of laboratory experiments is to provide reproducible and controllable experiment settings with more scientific and generalizable results. However, distraction in-the-wild is richer and more complicated (e.g., ambient noise, presence of other people in a public space, motor demand for walking or holding bags, etc.), and less controllable. Although controlling distractions in-the-wild is somewhat implausible, investigating alert perception through WTDs and relating it to distraction in-the-wild gives insight to the real world contribution of the research.

## ***7.4 Equalizing workload in secondary tasks***

In Chapter 5, alert perception using mobile phones is compared as the current practice. The two main factors that differentiate the WTD and current practice are information presentation modality (visual versus tactile) and form factor (handheld versus wrist worn). This difference is reflected in the difference of workload for alert perception: physical workload for the phone and mental workload for the WTD. In the current experiment, the effect



of each factor is unclear. Separating each factor would allow a more precise comparison. Specifically, visual and tactile alerts could be compared using the same wristworn device. Similarly, the same tactile alerts could be attempted using a device stored in the pocket versus worn on the wrist.

### ***7.5 Limitations of the Study***

Although the main focus of this dissertation was the perception of tactile stimuli on the wrist, two additional features were added while designing the experiments that may have affected the results: mapping the tactile patterns to visual representations (for the experiment in Chapter 4) and mapping the triangular layout of the vibrators to a linear layout of the keypad (for the experiment in Chapter 5) [70]. While the design choices were reasonable as verified through piloting and the follow-up study in Chapter 5, the full effect of these factors is unclear.

I also observed possible adaptation effects on the skin in the first experiment, and mechanical fatigue (e.g., eyes and legs) in the second experiment. A longitudinal study with fewer trials over multiple days would improve these issues.

Similar research that explored the perception of distinguishing different speeds between two tactile patterns on the wrist discovered a possible age confound between subjects over the age of 30 and those under the age of 30 [125]. Since the average age of participants in this work was mid-20s, performance of other age groups should be investigated to ensure that the patterns designed for the WTDs are applicable to all age groups.

## CHAPTER VIII

### CONCLUSION

Participants could discriminate four parameters (intensity, rhythm, direction, and starting point) to perceive 24 tactile patterns easily at up to 98% accuracy after 40 minutes of training. The easiest and hardest parameter to distinguish is rhythm and intensity, respectively.

In a dual task situation involving a time-constrained visual search task and the perception of three tactile alerts without time constraint, participants tended to prioritize the visual search task or temporarily set aside the tactile perception task before making a final decision (suggesting participants were using a selective attention paradigm).

The reaction time when perceiving the three different tactile alerts on the wrist was not slowed by visual distraction. In fact, given a small amount of visual distraction, a participant's engagement level seems to increase and facilitate faster reaction times. On the other hand, alerts presented using the screen of a mobile phone were consistently affected negatively by the visual search task.

Based on these results, I conclude that wrist-mounted tactile displays are appropriate for implementing multitasking-friendly mobile interactions that enable easy and eyes-free alert perception.

## APPENDIX A

### SURVEY MATERIAL

Study on Wearable Tactile Display

#### Survey & Questionnaires

Date. \_\_\_\_\_

No.	
Width (mm)	
Length (mm)	

1. Gender: \_\_\_\_\_
2. Age: \_\_\_\_\_
3. What is your dominant hand? \_\_\_\_\_
4. Do you usually wear a wristwatch or bracelet? 1) yes 2) no
  - a. If yes,
    - i. How often do you wear a wristwatch or bracelet?  
\_\_\_\_\_
    - ii. On which hand do you wear your wristwatch or bracelet?  
1) Dominant 2) Non dominant 3) other: \_\_\_\_\_
  - b. If no, why? \_\_\_\_\_
5. Please mark the difficulty level of perception for each parameter.
  - a. Starting point (1, 2, 3)  
1) Very easy 2) Easy 3) Not easy nor difficult 4) Difficult 5) Very difficult
  - b. Temporal pattern (steady / pulse)  
1) Very easy 2) Easy 3) Not easy nor difficult 4) Difficult 5) Very difficult
  - c. Intensity (weak / strong)  
1) Very easy 2) Easy 3) Not easy nor difficult 4) Difficult 5) Very difficult
  - d. Direction (CW / CCW)  
1) Very easy 2) Easy 3) Not easy nor difficult 4) Difficult 5) Very difficult
6. Did you have any strategy to learn or perceive tactile patterns? If so, what was your strategy? You can write it down at the other side of the paper or verbally explain to the researcher.

**Figure 70:** Survey material used in the experiment in Chapter 4

## Survey & Questionnaires

Date. \_\_\_\_\_

No.	
Width (mm)	
Length (mm)	

1. Gender: \_\_\_\_\_
2. Age: \_\_\_\_\_
3. What is your dominant hand? \_\_\_\_\_
4. Do you usually wear a wristwatch or bracelet? 1) yes 2) no
  - a. If yes,
    - i. How often do you wear a wristwatch or bracelet?  
\_\_\_\_\_
    - ii. On which hand do you wear your wristwatch or bracelet?  
1) Dominant 2) Non dominant 3) other: \_\_\_\_\_
  - b. If no, why? \_\_\_\_\_
5. Do you usually take your cell phone with you when you are not at home? 1) yes 2) no
  - a. If yes,
    - i. How often do you take your cell phone with you?  
\_\_\_\_\_
    - ii. Where do you carry your cell phone?  
\_\_\_\_\_
    - iii. Do you use your cell phone (e.g., answering/checking incoming message or phone call, making a phone call, checking calendar or time, playing game) while you are doing other task (e.g., walking, driving, talking, reading)? ( y / n )
      1. If yes, how often, and for which task? \_\_\_\_\_
      2. If no, why? \_\_\_\_\_
  - b. If no, why? \_\_\_\_\_
6. What do you think of mobile multitasking? Do you have any story regarding mobile multitasking?

**Figure 71:** Survey material used in the experiment in Chapter 5 (page 1 of 3)

7. Please briefly explain your experience from this test

		What was difficult?	What was easy?
Single	Primary task (Visual screening)		
	Secondary task 1 (Cell phone alert)		
	Secondary task 2 (Tactile display)		
Dual	Primary task (Visual screening)		
	Secondary task 1 (Cell phone alert)		
	Secondary task 2 (Tactile display)		

**Figure 72:** Survey material used in the experiment in Chapter 5 (page 2 of 3)

## 8. Modified NASA\_TLX

<Primary task: Visual Screening>

	Single	Dual
Mental Demand		
Physical Demand		
Temporal demand		

<Secondary task: Phone alerts>

	Single	Dual
Mental Demand		
Physical Demand		
Temporal demand		

<Secondary task: Wearable Tactile Displays>

	Single	Dual
Mental Demand		
Physical Demand		
Temporal demand		

**Figure 73:** Survey material used in the experiment in Chapter 5 (page 3 of 3)

## APPENDIX B

### HARDWARE SPECIFICATION

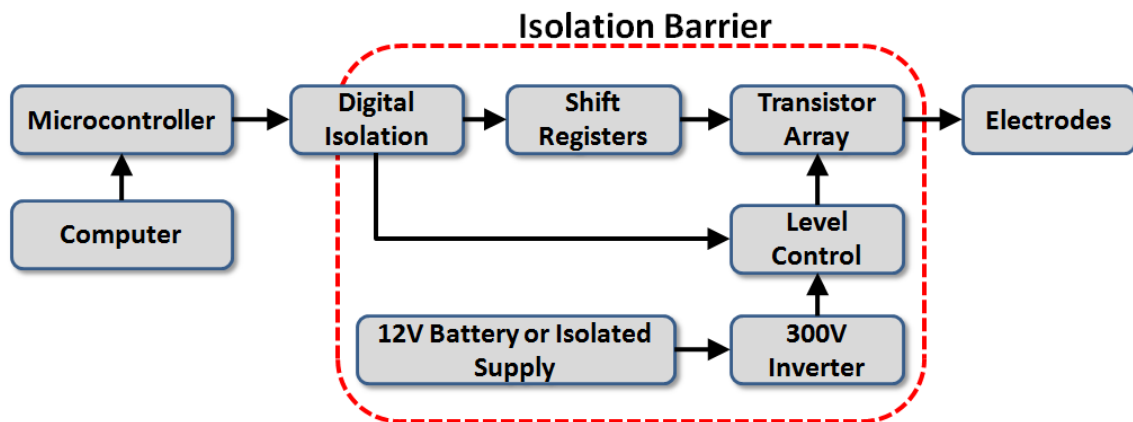
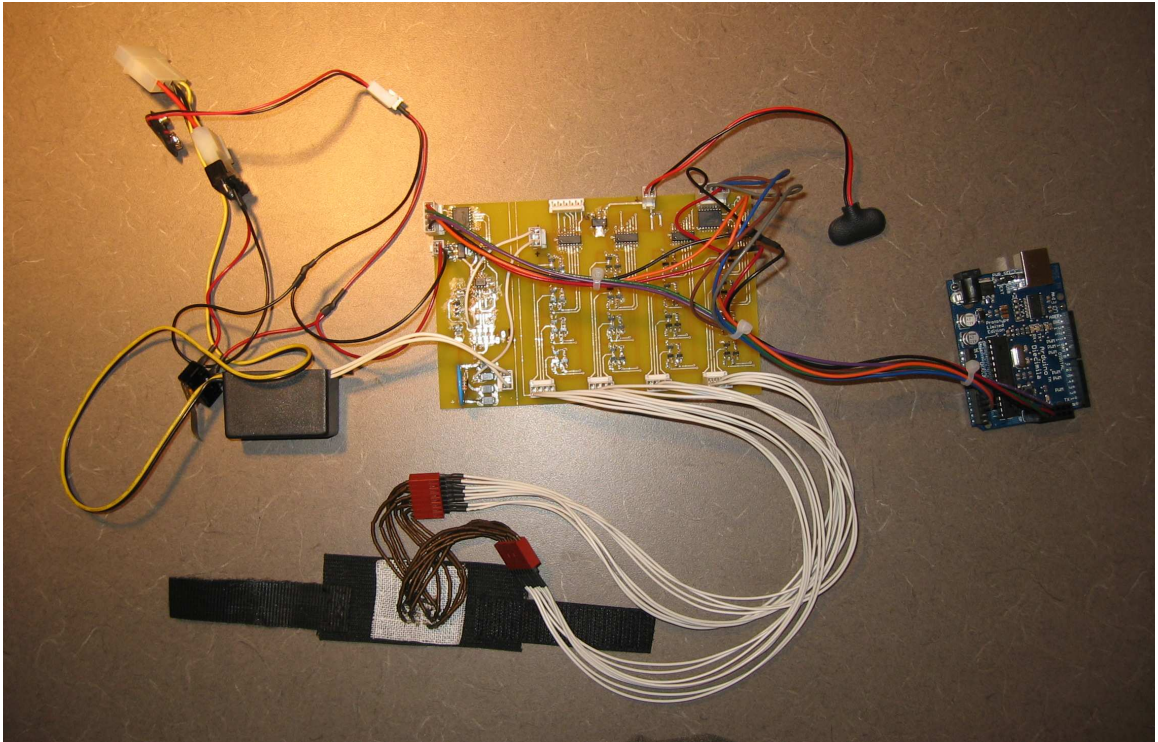


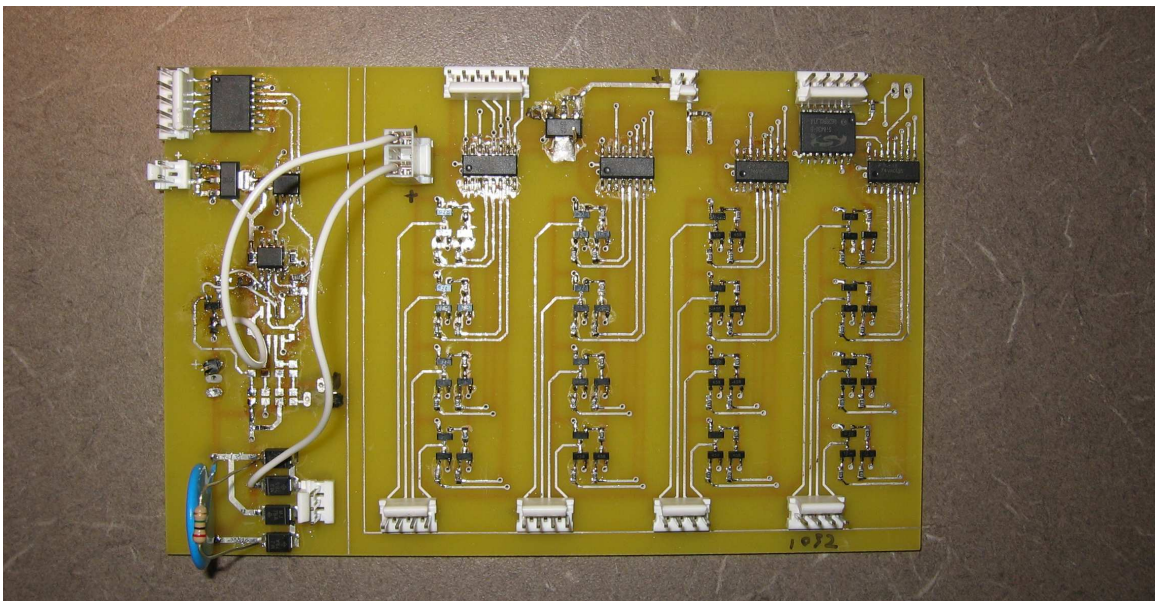
Figure 74: Block diagram of the electro-tactile display



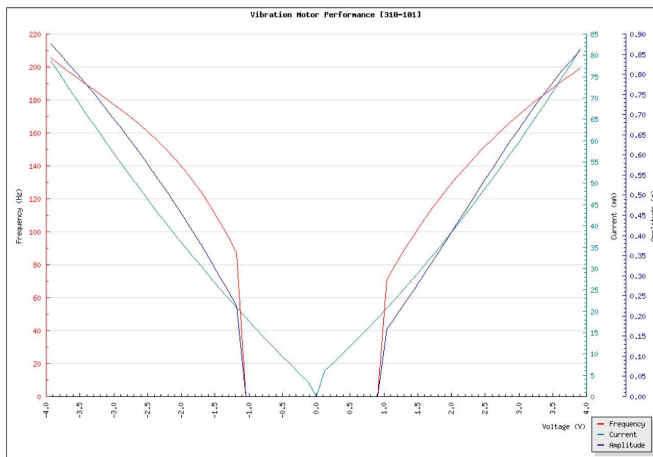
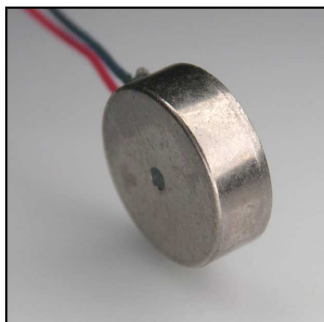
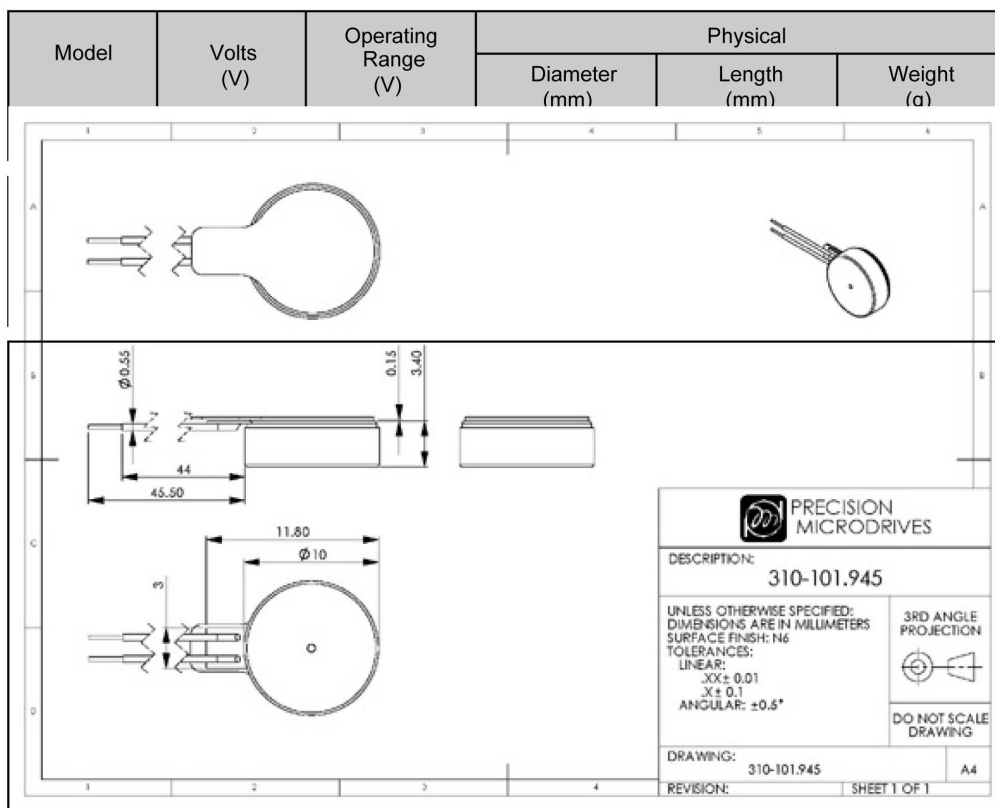




**Figure 76:** Overview of the apparatus of the electro-tactile display



**Figure 77:** Circuit board for the electro-tactile display



[www.precisionmicrodrives.com](http://www.precisionmicrodrives.com)

Tel: +44 (0) 1932 252482

Fax: +44 (0) 1932 325353

Email: [enquiries@precisionmicrodrives.com](mailto:enquiries@precisionmicrodrives.com)

Contact us for any volume enquiries, customisation and quotations. We offer performance matching, custom mounting and motor sourcing services

**Figure 78:** PrecisionMicrodrives #310-101 datasheet

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